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A SIMPLIFIED COMPUTER CODE FOR REDUCTION TO BURNING RATES OF CLOSED BOMB PRESSURE-TIME DATA (MINICB)

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TERESA GRIFFIE

AUGUST 1987

US ARMY BALLISTIC RESEARCH LABORATORY
ABERDEEN PROVING GROUND, MARYLAND

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TECHNICAL REPORT BRL-TR-2841

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DESTRUCTION NOTICE

Errata Sheet for BRL-TR-2841, " A SIMPLIFIED COMPUTER CODE FOR REDUCTION TO BURNING RATES OF CLOSED BOMB PRESSURE-TIME DATA(MINICB)"

Page	Description
v	Caption for Figure 4, second line: the burning
10	Equation 21: "[" after 'p *' and "]" at the end of the equation
80	Add the following equation at the end of the page:

$$x = a*M^3 + b*M^2 + c*M + d$$

REPORT DOCUMENTATION PAGE

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A closed bomb burning rate reduction code designed to operate on a microcomputer programmable hand calculator is presented. To accommodate the needs of a minimal computational environment simplifying assumptions were made in developing the theory form functions. Typically form function equations are valid only to the point of gra slivering. Evaluation of the program performed against synthetic data from a validat lumped parameter interior ballistics code (IBHVG2) indicates reasonable agreement wit overall mean error of 1.5% or less. The program also computes experimental impetus g the calculated value for co-volume. Keywords: mathematical models; computer program; computer applications; simulation;

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I. INTRODUCTION

The majority of information on the burning behavior of propellants used in interior ballistic gun simulations is obtained through burning samples of the propellant in a closed bomb. Analysis of the resulting pressure-time data, either in terms of burning rate information or experimental impetus, is of vital importance to the interior ballistician and propellant formulator. Highly sophisticated computer programs have been written to perform the needed burning rate analyses.[1][2] Results from these computations have proven to be extremely valuable in predicting propellant performance in guns. Such burning rate data, for instance, when used in two-phase-flow interior ballistic codes such as NOVA[3] have permitted prediction of not only gun muzzle velocities and peak chamber pressures but pressure oscillations as well.[4]

Unfortunately, sophistication is obtained at a price. Often the length or other requirements of the burning rate reduction program limit the equipment on which it can be used. In addition, program complexity often hinders quick turn around between closed bomb firings and data reductions. Finally, the intricate nature of the program can inhibit attempts at modification or extension. This final point is especially critical in research programs where some parameters, such as grain geometry, may fall outside the "normal range" accounted for in the program.

The drawbacks mentioned above have become apparent during the past several years in our work on new propellants for advanced ballistic applications. The program under discussion was written as an answer to these needs. In addition to burning rate computations, the program also calculates the propellant experimental impetus based on maximum experimental pressure, a highly useful feature in evaluating experimental performance of new formulations relative to their predicted thermodynamic performance via BLAKE.[5]

MINICB is offered as a practical tool for propellant formulators and combustion researchers to furnish quick feedback on results of closed bomb

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firings which could be used in guiding formulation efforts or combustion diagnostic work. Specifically, MINICB was developed to:

a. be simple and easy to operate.

b. be machine independent. In fact, MINICB will run on any computer using BASIC and on some programmable hand calculators.

c. be easily modified, especially in terms of non-standard grain geometry.

d. be usable with a full set of pressure-time data or a limited number of pressure-time points

e. be sufficiently accurate so as to provide useful information.

In this report we present the formulation of the underlying equations together with the simplifying assumptions which were used. Validation of the program and suggestions for implementation are also included.

II. DERIVATION OF EQUATIONS

BURNING RATE EQUATIONS

A. MASS FRACTION BURNT

In determining burning rates a sample of propellant together with an appropriate amount of igniter is ignited in a closed chamber. As the igniter and propellant burn the pressure within the chamber is recorded. Using the

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pressure-time history from the closed chamber, physical properties of the closed chamber, thermochemical properties of the igniter and propellant, and the grain geometry of the propellant, a relation between the burning rate of the propellant and pressure can be determined.

The burning rate analysis is a dynamic process in which calculations are performed stepwise along the pressure-time history of the burn. Mass and energy balance must be accounted for in the conversion of solid propellant to gaseous products. The process is not adiabatic since heat loss occurs to the walls of the chamber. The treatment of heat loss may be simplified, however, by assuming that it is a constant percentage throughout the burning cycle and that it can be accounted for by adjusting the theoretical gas temperature of the system by the ratio of the observed to theoretical maximum pressures.

Summarizing, the assumptions made in the burning rate analysis are presented below.

1. The original volume of the closed chamber is known.
2. The igniter is completely burnt before the propellant begins to burn.
3. The maximum pressure from the firing is known.
4. All thermochemical properties of the igniter and propellant are known.
5. The Noble-Able equation of state can be used to describe the state of the closed chamber.
6. The gas products of the igniter and propellant are thoroughly mixed at all times.
7. The rate of heat loss is constant throughout the burning process and can be represented as stated above.
8. The temperature of the system before heat loss can be given as a weighted average of the theoretical flame temperatures of the igniter and propellant gases.

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The burning rate analysis requires equations to describe the mass of propellant burned in the chamber at any given instant in terms of measured pressure and known parameters. To derive the required equations start with the Noble-Able equation of state.

$$P(V_b - b) = NRT \qquad (1)$$

Since the process is dynamic, the free volume of the bomb, V_b, will be constantly changing and is given by equation (2).

$$V_b = V - (C - C_p)/p_p - (C_{is} - C_i)/p_i \qquad (2)$$

Also, the co-volume correction term is given by,

$$b = n_i C_i + n_p C_p \qquad (3)$$

Now, recalling the assumption that the igniter is all burnt at the beginning of the analysis, hence, $C_i = C_{is}$, and substituting (2) and (3) into (1) gives equation (4).

$$P(V - C/p_p + C_p/p_p - C_p n_p - C_i n_i) = NRT \qquad (4)$$

Assuming a well mixed combination of the gases from the igniter and propellant,

$$N = N_i + N_p \qquad (5)$$

equation (4) becomes:

$$P(V - C/p_p + C_p/p_p - C_p n_p - C_i n_i) = RT(N_i + N_p) \qquad (6)$$

Next using the relation, number of moles = weight/molecular weight, to modify equation (6).

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$$P(V - C/p_p + C_p/p_p - C_p n_p - C_i n_i) = RT(C_p/m_p + C_i/m_i) \qquad (7)$$

Now equation (7) can be solved for C_p.

$$C_p = \frac{P[V - C/p_p - C_i n_i] - (RT/m_i)C_i}{(RT/m_p) + P[n_p - 1/p_p]} \qquad (8)$$

The term T in equation (8) stands for the system gas temperature. In an adiabatic system this would be a weighted average for the igniter and propellant flame temperatures with suitable provisions for differences in their respective heat capacities. Assuming equivalent heat capacities for propellant and igniter combustion products, it can be approximated as

$$T = \frac{CT_p + C_i T_i}{C + C_i} \qquad (9)$$

Assuming further that the experimental shortfall of pressure is entirely due to cooling of the gaseous combustion products, the system temperature may be approximated as

$$T = \frac{CT_p + C_i T_i}{C + C_i} * \frac{Pmax}{Ptheo} \qquad (10)$$

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For systems where the amount of propellant is much greater than the amount of
igniter, T may be approximated throughout as a constant defined by the all-
burnt condition of equation (10). Ptheo is computed using the Noble-Able
equation of state with the igniter and propellant all burnt. This is equation
(11) given below.

$$Ptheo = \frac{RT_iC_i/m_i + RT_pC/m_p}{(V - n_iC_i - n_pC)} \qquad (11)$$

One last simplification can be made to several of the equations by using the
following expression for impetus of the igniter.

$$F_i = RT_i/m_i \qquad (12)$$

Equation (11) can be rewritten as

$$Ptheo = \frac{F_iC_i + RT_pC/m_p}{(V - n_iC_i - n_pC)} \qquad (13)$$

and equation (8) for the mass of propellant burned at any instant becomes

$$C_p = \frac{P[V - C/p_p - C_in_i] - (F_iT/T_i)C_i}{(RT/m_p) + P[n_p - 1/p_p]} \qquad (14)$$

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Having derived the equation for the mass of propellant burned at any instant in terms of measured pressure and known variables, several approaches to computing burning rate are possible. These are all predicated on our ability to further describe the mass of propellant burned in terms of geometric changes in the burning propellant grains. For example, if x represents the distance burned and A the surface area of the propellant when x is the distance burned then

$$C_p = A * x * p_p \tag{15}$$

or

$$x = C_p/A*p_p \tag{16}$$

Finally, differentiating both sides of (19) with respect to time gives an expression for the burning rate, r.

$$r = dx/dt = (dC_p/dt)/A*p_p \tag{17}$$

This is the approach which will be followed here since knowledge of the instantaneous surface area is a valuable tool in analyzing and understanding closed bomb results. Alternately, x, the distance burned, hence burning rate, could be expressed in terms of the mass fraction of propellant burned without invoking surface area at all. That technique, particularly suited to hand calculators, is covered in Appendix E.

B. SURFACE AREA

In computing the burning rate, r, in equation (17) the value for the surface area, A, must be known at each time step the calculations are being performed. For this program the surface area is calculated using the following scheme.

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1. The amount of propellant burnt, C_p, is equal to the
   density times the volume of propellant burnt.

2. The volume of propellant burnt is determined from the
   initial dimensions of the propellant grain and the
   linear depth burnt, which is denoted by x.

3. From 1 and 2, C_p is a function of initial propellant
   grain dimensions, density, and depth burnt.

4. Thus, the depth burnt can be solved for in terms of
   initial grain geometry, amount burnt, and density.

5. The surface area at any time is a function of initial
   grain geometry and depth burnt at that time.

To illustrate the scheme, the formula used in MINICB for the surface area
of a single perf grain will be derived. The derivation of other surface area
equations can be found in Appendix A and in the text by Hunt.[6] For the
derivation let the propellant density be given by p instead of p_p.

Figure 1. shows a single perforated grain after it has burnt a linear
distance, x, on all surfaces. The volume used or burnt is given in equation
(18).

$$\text{Volume Used} = L*Pi*[(D/2)^2 - ((D - 2x)/2)^2]$$

$$+ L*Pi*[((d + 2x)/2)^2 - (d/2)^2]$$

$$+ 2x*Pi*[((D - 2x)/2)^2 - ((d + 2x)/2)^2] \tag{18}$$

In equation (18), the first term represents the volume used along the outer
lateral surface and the second term, the volume along the lateral perf
surface. The final term is the additional volume lost from the ends not
accounted for in the other two terms. Another approach to determining the
volume used would be to take the original volume and subtract the volume

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remaining after the grain had been burnt a depth x. The two approaches are equivalent and lead to the same equations.

Simplifying, equation (18) becomes

$$\text{Volume Used} = L*Pi*[xD - x^2] + L*Pi*[xd + x^2]$$
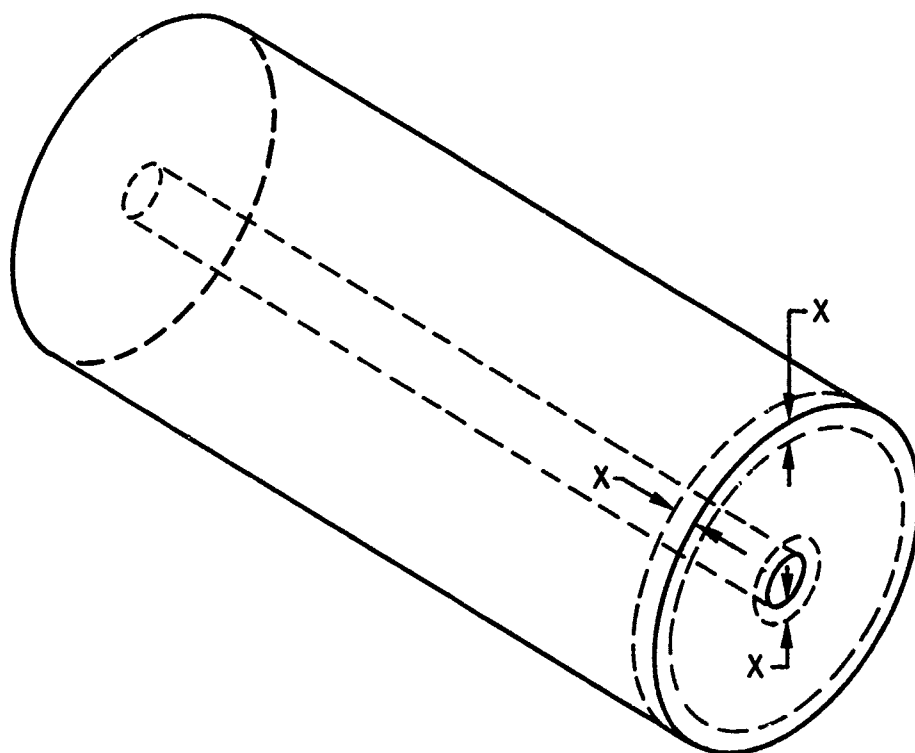
$$+(x*Pi/2)*[D^2 - d^2 - 4xD -4xd] \tag{19}$$

Figure 1. **A single perf grain which has burnt a distance, x, on all surfaces.**

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Now the total amount of propellant burnt can be expressed in the following relation.

$$C_p = p * \text{Volume Used} \qquad (20)$$

Substituting (19) into (20)

$$C_p = p * L*Pi*[xD - x^2] + L*Pi*[xd + x^2]$$

$$+(x*Pi/2)*[D^2 - d^2 - 4xD - 4xd] \qquad (21)$$

At this point equation (21) can be solved for x which then can be used to determine the surface area. Expanding and rearranging

$$2*C_p/(L*p) = (-4D - 4d)*x^2 + (-d^2 + D^2 + 2LD + 2Ld)*x \qquad (22)$$

This is now a quadratic equation in x and can be solved using the quadratic formula. First, rearrange equation (22).

$$(4D + 4d)*x^2 - (-d^2 + D^2 + 2LD + 2Ld)*x + 2*C_p/(L*p) = 0 \qquad (23)$$

Let AA = 4D + 4d, BB = $(-d^2 + D^2 + 2LD + 2Ld)$, and CC = $2*C_p/(L*p)$, then

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$$x = \frac{BB +- \sqrt{(-BB)^2 - 4*AA*CC}}{2*AA} \qquad (24)$$

At this point it is necessary to determine which root corresponds to the correct value of x. Several observations:

1. AA and CC are both positive.
2. BB is positive since D is large than d.
3. The radical must be real since a solution must exist.
4. The radical is always less than BB since $4*AA*CC$ is positive and is subtracted from BB^2.
5. Based upon 1 - 4, there are two positive real roots for x.
6. Now, x should be the smaller of the roots. If x was the larger root then the smaller root would also be a valid solution. However, this would result in two possible solutions which is physically not possible.
   Thus, x must correspond to the root with the negative sign.

Therefore,

$$x = \frac{BB - \sqrt{(-BB)^2 - 4*AA*CC}}{2*AA} \qquad (25)$$

Referring to Figure 1, the surface area of the grain corresponding to a depth x burnt is given in equation (26).

$$A = (L - 2x)*Pi*[D - 2x] + (L - 2x)*Pi*[d + 2x]$$

$$+ 2*Pi*[((D - 2x)/2)^2 - ((d + 2x)/2)^2] \tag{26}$$

This equation can now be used to determine the surface area of the grain for a given depth burnt.

Summarizing, the burning rate is given by equation (17)

$$r = dx/dt = (dC_p/dt)/A*p_p \tag{17}$$

To determine the rate the following procedure is used.

1. From equation (14) C_p can be determined for each value of pressure in the pressure-time history.
2. The values for dC_p/dt can be determine from C_p using a numerical technique.
3. Using equation (26) or a similar one for the appropriate grain geometry the values for the instantaneous surface area can be determined for each value of C_p determined in 1.
4. Since p_p is a constant, the burning rate can now be readily calculate from equation (17).

EXPERIMENTAL IMPETUS

The traditional approach for determining experimental impetus is presented by Hunt[6] in his text on interior ballistics. Exact details can be found in Appendix D. This method requires a series of closed bomb firings with different loading densities. In some propellant research efforts, where burning rate is of primary interest and sample amounts are limited, it is

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often not practical to fire such a series. If a reasonably accurate value of the propellant co-volume can be obtained, however, then a reliable measure of experimental impetus may be obtained with a single closed bomb firing.

In propellant development efforts it is general practice to calculate theoretical thermodynamic properties for a proposed formulation based on its chemical composition and the heats of formation of its ingredients. In this way, theoretical values for impetus, co-volume, molecular weight of combustion products and the like are available for new formulations from computations using codes such as BLAKE. However, these theoretical thermodynamic values still need to be verified. Fortunately, while impetus is strongly sensitive to composition, co-volume is not. As stated by Hunt,

> "..., since impetus is sensitive to slight variations
> in propellant composition, particularly in the
> moisture content, the experimental values of impetus
> should be more reliable than the calculated values.
> The co-volume, on the other hand, is not sensitive to
> small changes in composition and can only be
> derived experimentally by a difference process; the
> calculated values are therefore more reliable."

The co-volumes computed by BLAKE, therefore, can be assumed as reasonable for most systems, except for those having high levels of condensable combustion products (metal oxides/ nitrides/ sulfides/ sulfates and their derivatives). The experimental impetus computations described below are predicated on the assumption that BLAKE co-volumes are reasonably correct for the formulation.

In determining experimental impetus a sample of propellant together with an appropriate amount of igniter is completely burned in a closed chamber of known volume. The pressure-time history, including maximum observed pressure, is recorded. Based upon the maximum pressure, the closed chamber volume, thermochemical properties of the igniter, and co-volume of the propellant an

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experimental impetus can be determined. (Data from the same experiment can also be used for burning rate computations). The method works best for fast-burning samples where heat loss is small.

In deriving the equation for computing the experimental impetus the following assumptions have been made in order to meet the objectives stated in the introduction.

1. The original volume of the closed chamber is known.
2. Both the igniter and propellant are completely burnt.
3. The maximum pressure from the firing is known.
4. All thermochemical properties of the igniter are known.
5. The co-volume of the propellant is known.
6. The Noble-Able equation of state can be used to describe the final state of the closed chamber.
7. The theoretical impetus of the igniter can be used in place of the experimental impetus of the igniter.

For a closed chamber with free volume, V_b, the Noble-Able equation of state is

$$P(V_b - b) = NRT \qquad (27)$$

where P = pressure
    b = co-volume correction term
    N = number of moles of gas
    T = system temperature
    R = universal gas constant

Since all igniter and propellant is assumed to be completely burnt, the free volume of the chamber, V_b, is the volume of the empty chamber, V. Also, having all igniter and propellant burnt implies that the co-volume correction term, b, is the sum of the product of the co-volume and weight for the igniter

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and propellant. That is,

$$b = n_i C_i + n_p C \tag{28}$$

Substituting into (27) yields

$$P(V - n_i C_i - n_p C) = NRT \tag{29}$$

Now the gas in the chamber is a mixture of gas products from the igniter and the propellant. Thus, $N = N_i + N_p$ which when substituted into (29) produces the following equation.

$$P(V - n_i C_i - n_p C) = RT(N_i + N_p) \tag{30}$$

Multiplying the right-hand side of (30), equation (31) is obtained.

$$P(V - n_i C_i - n_p C) = RTN_i + RTN_p \tag{31}$$

Since $N =$ weight divided by molecular weight, N_i and N_p can be replaced to obtain

$$P(V - n_i C_i - n_p C) = RTC_i/m_i + RTC/m_p \tag{32}$$

Now impetus is given by the formula

$$F = RT/m \tag{33}$$

Thus, using the assumption that the theoretical impetus of the igniter can be used in place of the experimental impetus together with (33) the expression below is obtained.

$$P(V - n_i C_i - n_p C) = C_i F_i + C F_p \tag{34}$$

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Finally, equation (34) can be solved for the experimental impetus of the propellant.

$$F_p = [P(V - n_iC_i - n_pC) - C_iF_i]/C \qquad (35)$$

III. MINICB - PROGRAM

Program Flow

The flow of the program MINICB is presented below.   A complete listing of the program together with a listing of variables used in it can be found in Appendix B.

①———————▶ Enter Time Step, Select Grain
Form Function, and Enter
Pressure Data

Print Input Information and
Maximum Observed and Theoretical
Pressures (Not used in hand
calculator version)

Smoothing Pressure Data to
Ensure Increasing Pressure
(Not used in hand calculator
version)

Computation of Total Propellant
Burnt at the End of Each Time
Step

Computation of dP/dt and dC/dt
with or without using a five
point differentiation bridge
(Not used in hand calculator
version)

Computation of Surface Area
From Form Function
(Not used in hand calculator
version)

②◀——————— Computation of Burning Rates

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Except for the five point differentiation the calculations used in MINICB were described in section II. As for the five point differentiation method it was obtained from a paper by Juhasz and Price[7] and is given by the following formula.

$$dP_0/dt = \frac{-2*P_{-2} - P_{-1} + 0 + P_{+1} + 2*P_{+2}}{10*\Delta t} \qquad (36)$$

In the formula P_{-2}, P_{-1}, P_0, P_{+1}, and P_{+2} are five successive points in the data set and the derivative of the pressure is to be estimated at the pressure value of P_0.

RUNNING MINICB

To run MINICB, load the program MINICB and run it from BASIC. For the most part MINICB is menu driven and will only require entering the necessary values for whatever computation is to be performed. The input values needed for each option are listed below in Tables 1 and 2 together with the units for each input value.

TABLE 1. Required Input for the Experimental Impetus
Calculation

Flame Temperature of Igniter -- Degrees Kelvin

Molecular Weight of Igniter

Co-volume of Igniter -- Cubic Inch/lb.

Weight of Igniter -- Pounds

Theoretical Impetus of Igniter -- FT.-lb./lb.   Optional

Weight of Propellant -- Pounds

Co-volume of Propellant -- Cubic Inch/lb.

Observed Maximum Pressure -- Psi

Volume of Closed Chamber -- Cubic Centimeters

TABLE 2. Required Input for the Burning Rate
Analysis

Theoretical Impetus of Igniter -- Ft.-lb./lb.   Optional

Flame Temperature of Igniter -- Degrees Kelvin

Molcular Weight of Igniter

Co-volume of Igniter -- Cubic Inch/lb.

Weight of Igniter -- Pounds

Weight of Propellant -- Pounds

Co-volume of Propellant -- Cubic Inch/lb.

Flame Temperature of Propellant -- Degrees Kelvin

Molecular Weight of Propellant

Density of Propellant -- lb./Cubic Inch

Length of Propellant Grain -- Inch

Diameter of Propellant Grain -- Inch

Perf Diameter of Propellant Grain -- Inch

Inner Web of Propellant Grain -- Inch

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TABLE 2. Required Input for the Burning Rate
Analysis (Con't)

Middle Web of Propellant Grain -- Inch

Outer Web of Propellant Grain -- Inch

Number of Perfs

Form Function

Observed Maximum Pressure -- Psi

Volume of Closed Chamber -- Cubic Centimeters

Delta Time -- Msec

Starting Time -- Msec

Pressure Data -- Psi

The pressure data, at fixed time intervals, can be entered by hand or
read from a file stored on a disk. In either case, the pressure values are
entered one per line with the last value being a -1 to terminate the input.
The input should not contain time, this information is generated from knowing
delta time and the starting time. Also, the pressure should always be
increasing. If the pressure is not increasing then the program will produce
negative burning rates (physically not meaningful) for those times where the
pressure decreases. The negative burn rates reflect the fact that in the
analysis a decrease in pressure means an increase in solid propellant, not
heat loss, which is accounted for by an adjusted system temperature.

Output from MINICB is, of course, dependent upon which type of
calculation is being performed. For the experimental impetus calculation the
output is a one page summary of the input values together with the computed
experimental impetus for the propellant given in Joules/gram and Ft.-lb./lb.
The output for the burn rate analysis is in two parts. The first is a

hardcopy to the printer which consists of a summary of the input values, the theoretical maximum pressure, number of propellant grains and an optional table of burning rates at every 500 psi. The second form of output is a disk file which consists of a table containing time, pressure, dP/dt, percent burnt, burning rate, and surface area fraction. This file will also contain the table of burning rates at every 500 psi if the option was selected. Samples of the output available from MINICB are given in Appendix C.

IV. VALIDATION

Validation of MINICB requires an assessment of its performance in computing burning rates with its various form functions as well as in computing experimental impetus. The procedures followed and results obtained are given below.

Burning Rate Validation

A well-tested lump parameter interior ballistic code, IBHVG2,[8] was used to simulate closed bomb burning by making the projectile weight so large that no projectile motion occurred. This permitted direct quantitative comparison of MINICB burning rate outputs with the burning rate inputs used to generate the pressure-time data up to the point of Pmax. In addition, the results from MINICB were found to be in reasonably close agreement with experimental burning rate data computed by CBRED[1] (See Appendix G and Table F-3, Appendix F).

At the present time, MINICB contains five different form functions for grain geometry. These form functions are:

1. Cord burning cigarette fashion -- burning on one end only
2. Single perf burning only on the perf surface
3. Single perf grain

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4. Generalized n-th perf grain -- the form function assumes all webs are equal and all perf diameters are equal. In addition, the form function only holds up to the point of slivering.

5. Single perf burning on both ends and the perf surface

All five form functions were exercised, see validation runs 1-5 below. For the general n-th perf grain a seven perf case was chosen. More details concerning the form functions can be found in Appendix A.

Propellants A, B, and C with bP^n burning rate laws and realistic thermochems were used for the simulations. The values of b and n as well as the propellant/igniter thermochemical data used in the various simulations are given in Tables 3 - 5.

TABLE 3. Details of propellant and igniter used in IBHVG2 to simulate closed bomb firings for validation runs 1, 2 and 3.

	Propellant	Igniter
Type:	A	------
Coefficient b	0.0826	------
Exponent n	0.865	------
Weight(lb):	0.0165	0.000001
Density(lb/in^3):	0.056	------
Gamma:	1.2386	1.2386
Impetus(ft-lb/lb):	347243	347243
Co-volume(in^3/lb):	26.62	26.62
Flame Temperature(K):	3092	2000

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TABLE 4. Details of propellant and igniter used in IBHVG2 to simulate closed bomb firings for validation 4.

	Propellant	Igniter
Type:	B	Black Powder
Coefficient b	0.001216	------
Exponent n	0.865	------
Weight(lb):	0.1213	0.00441
Density(lb/in^3):	0.0596	------
Gamma:	1.2256	1.25
Impetus(ft-lb/lb):	361059	96000
Co-volume(in^3/lb):	27.261	30.00
Flame Temperature(K):	3289	2000

TABLE 5. Details of propellant and igniter used in IBHVG2 to simulate closed bomb firings for validation 5.

	Propellant	Igniter
Type:	C	Black Powder
Coefficient b	0.001216	------
Exponent n	0.865	------
Weight(lb):	0.1213	0.00441
Density(lb/in^3):	0.0585	------
Gamma:	1.238	1.25
Impetus(ft-lb/lb):	359671	96000
Co-volume(in^3/lb):	28.482	30.00
Flame Temperature(K):	3119	2000

23

Validation 1. The burning of propellant A, see Table 3, with a cord geometry burning cigarette fashion (i.e. on a single end surface) was simulated via IBHVG2 and reduced via MINICB. In place of showing all the output from MINICB, the results will be displayed graphically showing the percent difference between the burning rates calculated by MINICB and the actual burning rates as given by the burning rate law $r = .0826P^{.865}$ for different values of pressure, see Figure 2. Agreement between the burning rate values extracted and the initial burning rate values was close for the entire burn, with a mean error of 0.57 percent.

CIGARETTE FORM FUNCTION

PERCENT DIFFERENCE
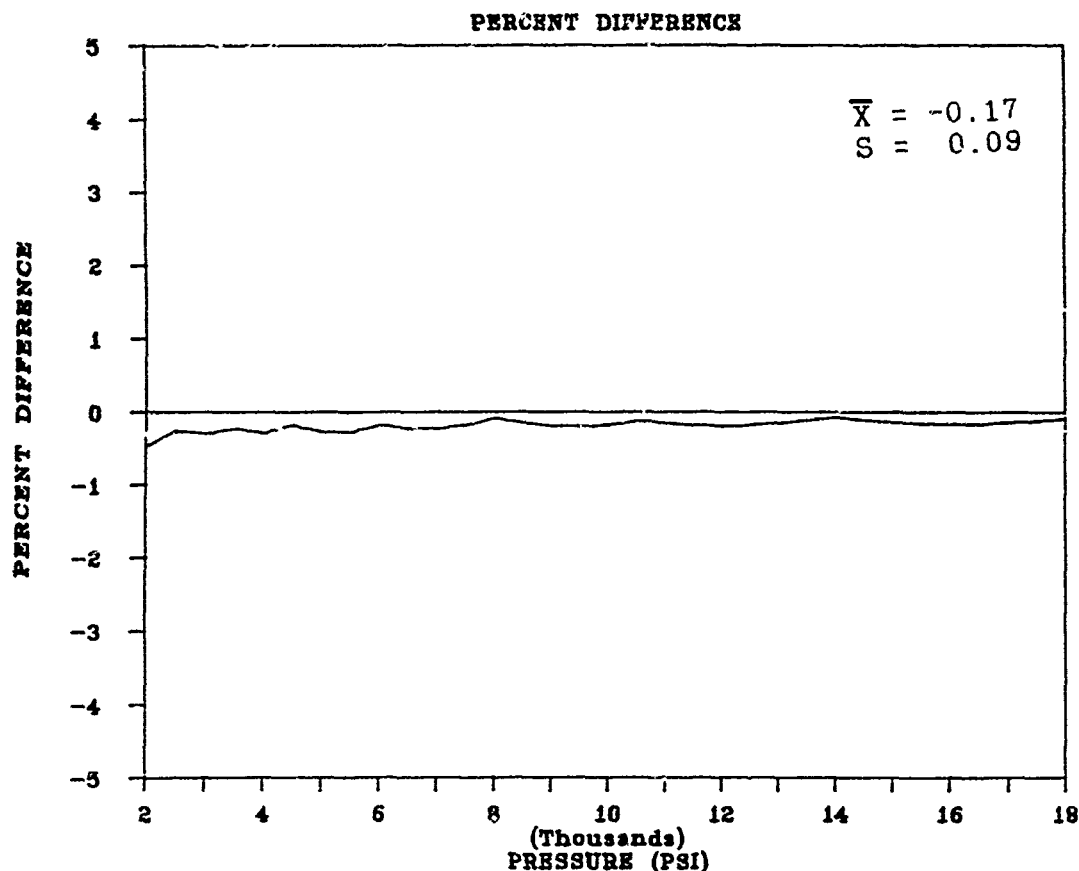
Figure 2. Percent difference between computed burn rates from MINICB and theoretical burning rates for a cord burning in a cigarette fashion, Validation 1.

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Validation 2: Propellant A, Table 3, single perforated grain, burning only on the perforation surface. Results similar to the first case are presented below in Figure 3. In this case the mean error was -.87 percent.

BURNING ON PERF SURFACE ONLY

PERCENT DIFFERENCE

$$\overline{X} = -0.87$$
$$S = 0.35$$
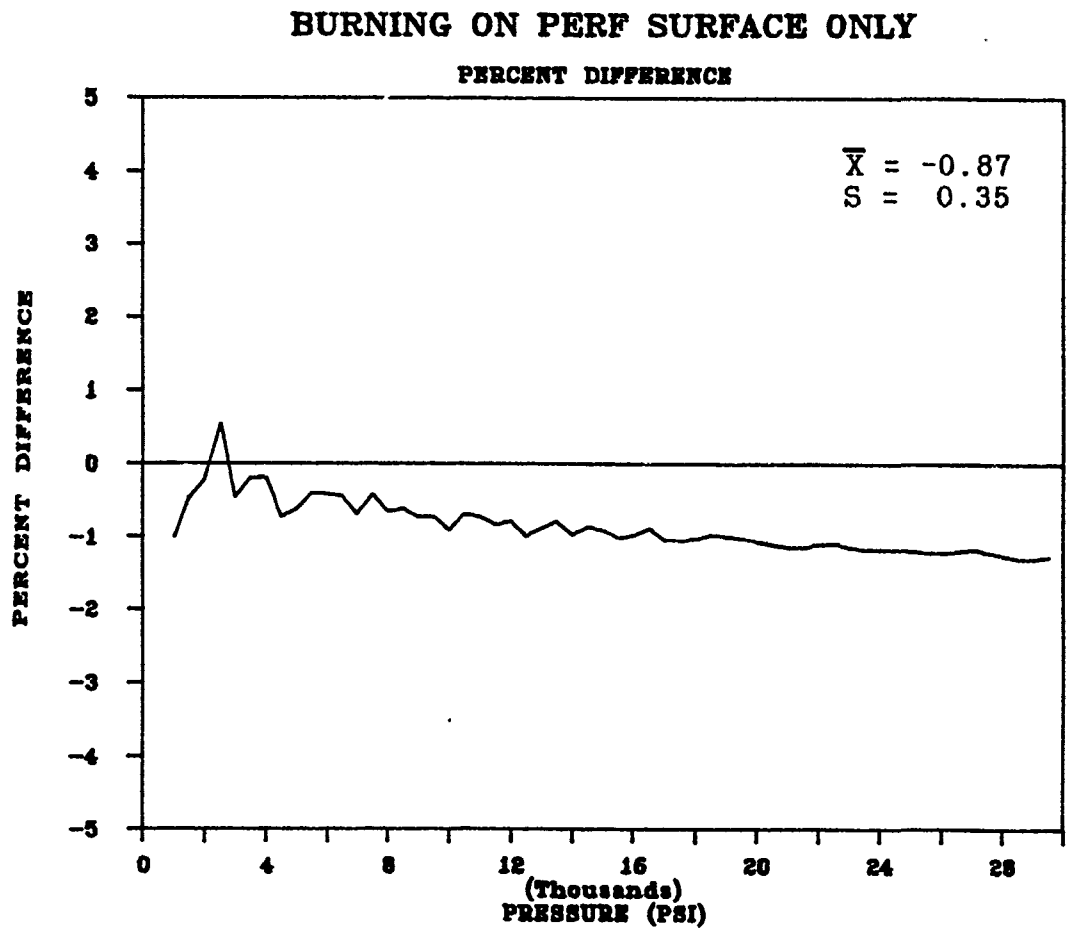
Figure 3. <u>Percent difference in burning rates between MINICB and rates computed using the burning rate law for a single perf grain burning on the perf surface only, validation 2.</u>

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Validation 3. Propellant A, single perforated geometry, burning on the ends and the perforation surface. Results similar to those above are given in Figure 4. In this case the mean error was 1.69 percent. The error, however, was increasing near the end of the burn, reaching a maximum of 4 percent at burnout.

BURNING ON PERF & END SURFACE

PERCENT DIFFERENCE

$\overline{X} = 1.69$
$S = 0.9$
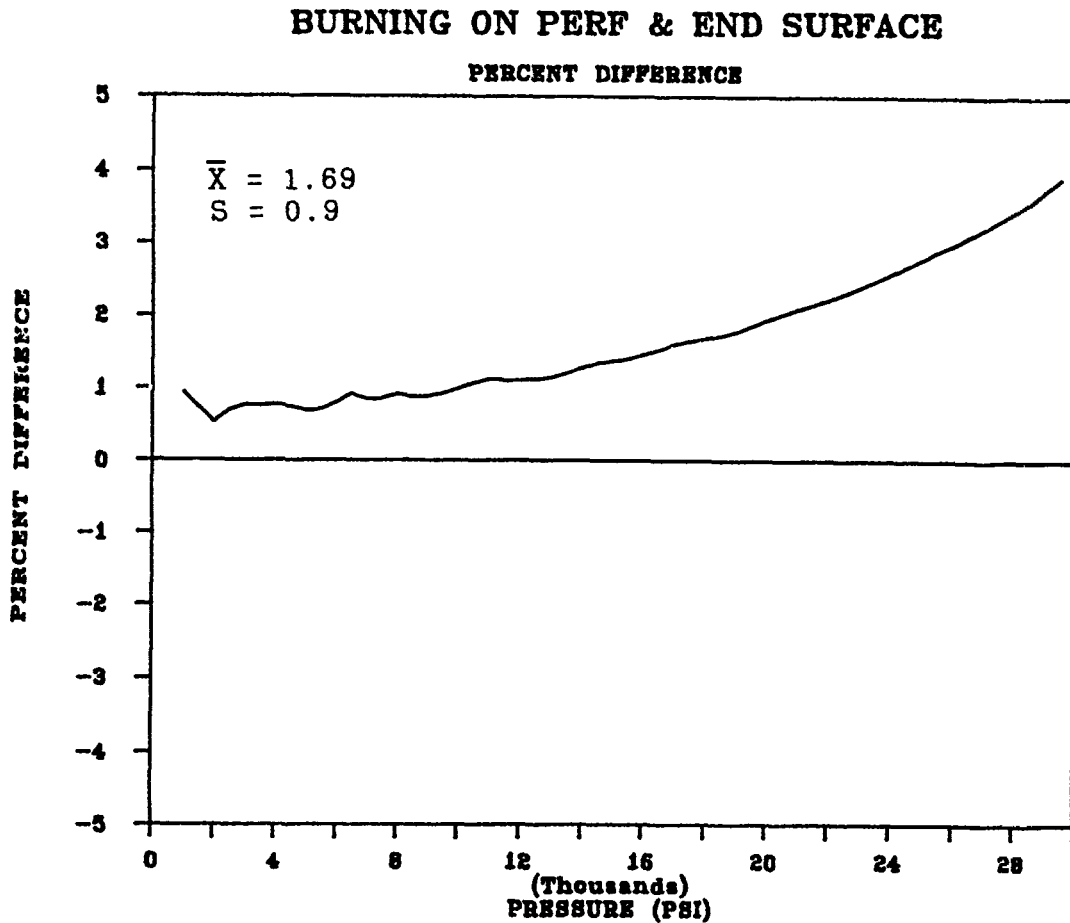
Figure 4. Percent difference in burning rates between MINICB and rates computed using the burning rate law for a single perf grain burning on the ends and perf surface, validation 3.

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Validation 4. Propellant B, Table 4, single perforated geometry burning on all surfaces. Results are agin presented in terms of percent differences in Figure 5. In this case the difference between the derived and initial burning rates was reasonably constant, averaging 1.35 percent.

SINGLE PERF GRAIN

PERCENT DIFFERENCE

$\overline{X} = 1.35$
$S = 0.27$
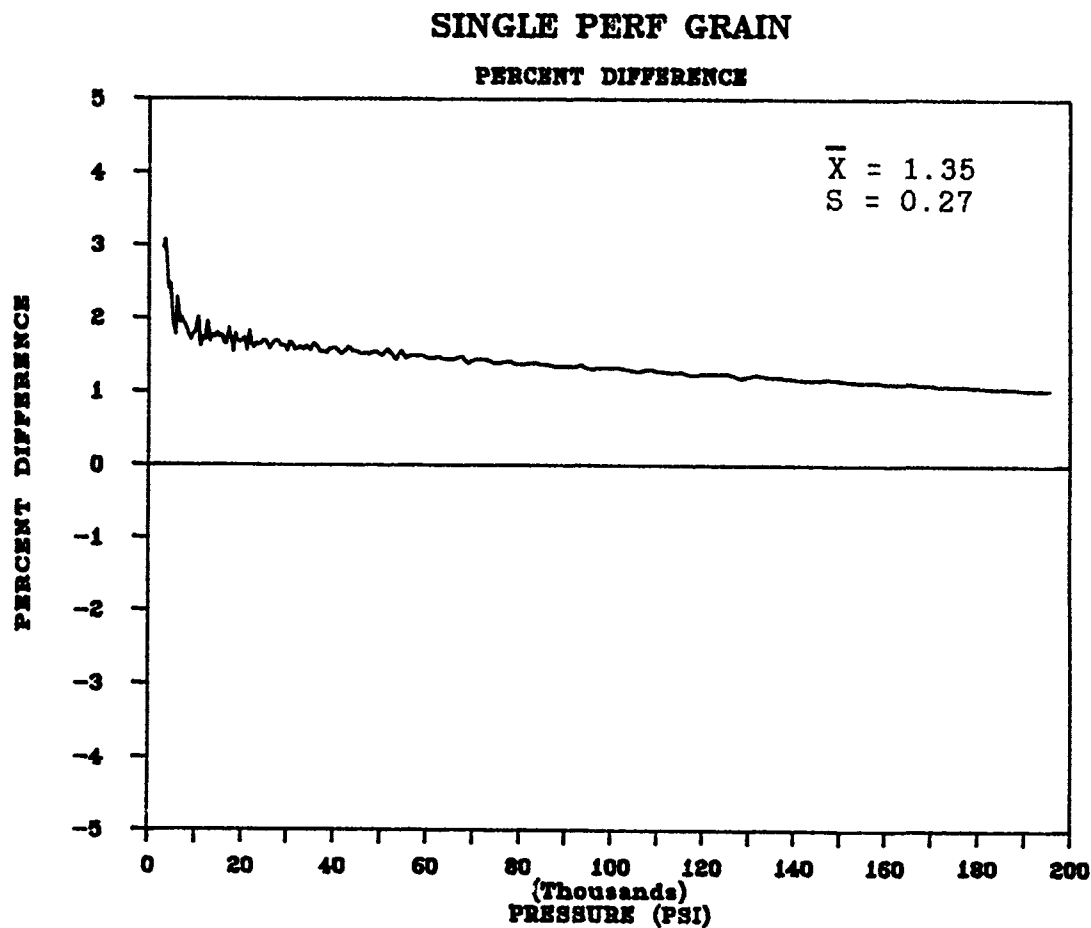
Figure 5. <u>Percent difference in burning rates between MINICB and rates computed using the burning rate law for a single perf grain, validation 4.</u>

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Validation 5.   Propellant C, Table 5, seven perforated grain burning on all surfaces.   Results are presented in the same manner as above in Figure 6.   The burning rates computed were approximately two percent high initially and 1.75 percent low at the end of the analysis which was performed to the point of grain slivering.   The overall absolute mean error was 0.88 percent.

SEVEN PERF GRAIN

PERCENT DIFFERENCE

$$\overline{X} = -0.45$$
$$S = 0.9$$
$$|\overline{X}| = 0.88$$
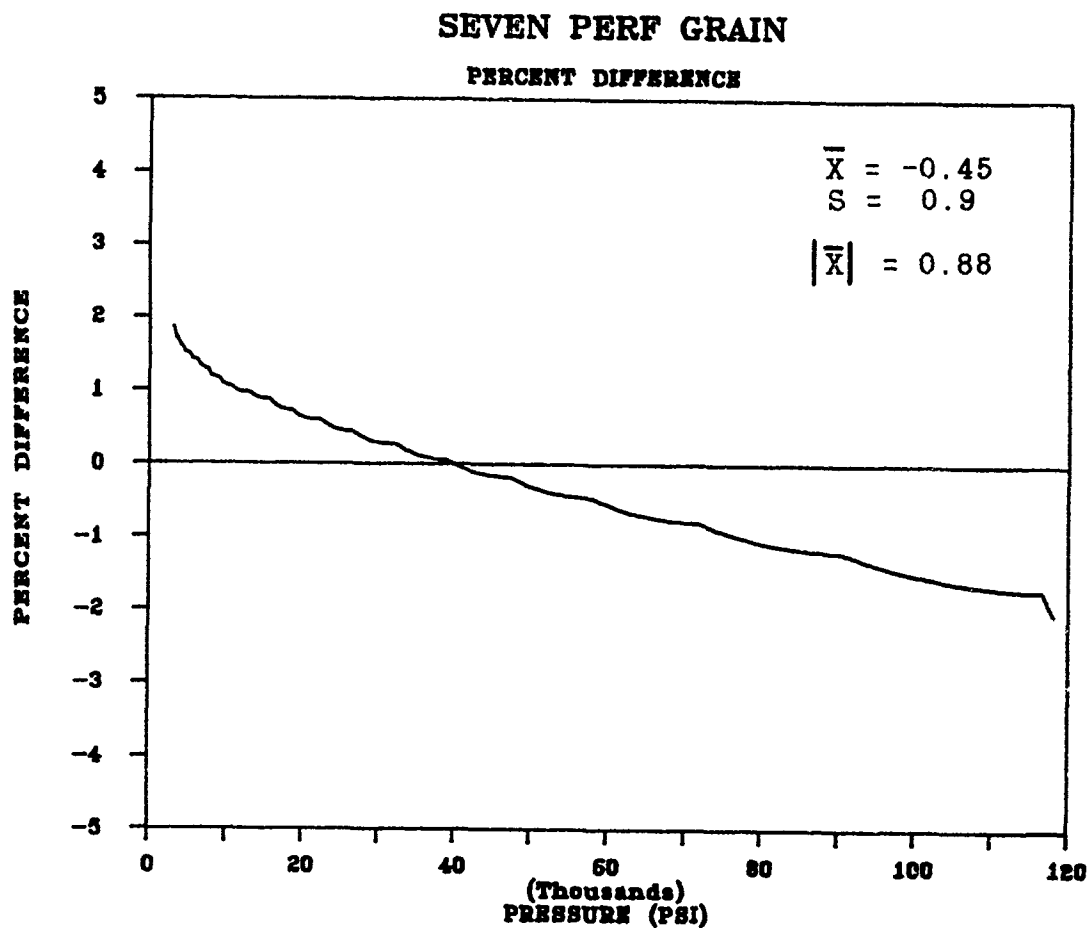
Figure 6.   Percent difference in burning rates between MINICB and rates computed using the burning rate law for a seven perf grain, validation 5.

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Overall, for the different form functions, the average error is less than two tenths of one percent in the best case and below 1.4 percent in the worst case. On the 5 to 95% interval of Pmax the greatest observed error was ~3%. Due to the lower level of error in the constant area case, it seems probable that numerical errors are magnified during the surface area computations. The error levels above fall within the normal experimental round-to-round variation of closed bomb burning rates and, therefore, are not overly critical. Considering the simplifying assumptions made in developing the theory and the crude numerical methods used, the error levels appear reasonable for the intended application. MINICB was designed as a quick tool for determining burning rates from a limited number of pressure points. The simplifications introduced were necessary to permit running in a minimum environment.

Burn Rate Error vs. Number of Data Points

Since MINICB can be run using a programmable calculator or a computer with pressure information entered by hand, it was of interest to investigate what effect the number of pressure values entered would have on program performance. The data set for the end-burning cord, see verification run 1 for details, was reduced via MINICB using different numbers of pressure values. In all instances, points were selected at equal intervals and included the original first pressure value as well as the maximum pressure value. Data sets containing 253, 126, 64, 22, or 12 points were used. The results are presented in terms of percent difference and mean and standard deviation of percent difference, see Figure 7 and Table 6.

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CIGARETTE FORM FUNCTION
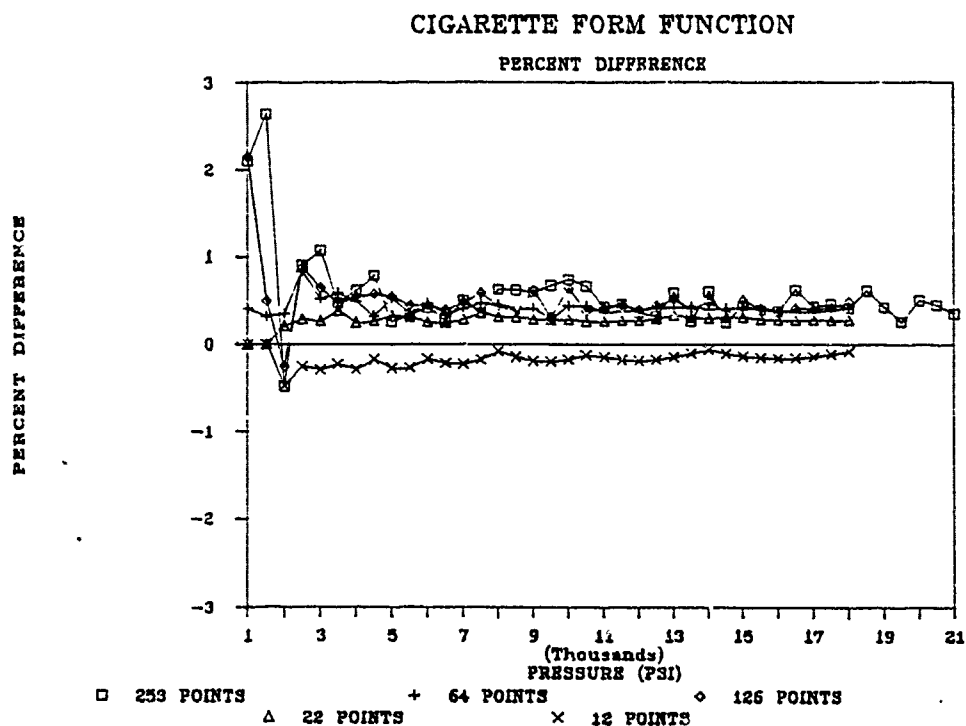
Figure 7.   <u>Percent Difference in burning rates between</u>
<u>MINICB and theoretical burning rates for a cord</u>
<u>burning in a cigarette fashion for data sets</u>
<u>with different number of points where each</u>
<u>set was taken from the same original data set.</u>

TABLE 6.   Mean and standard deviation of percent
error for data sets with different number
of points all of which were taken from
the same original data set.

Number of Points	Mean	Standard Deviation
253	.567233	.474999
126	.504159	.325364
64	.42504	.093079
22	.274162	.074713
12	-.17125	.086029

Paradoxically, as the number of data points in the set decreased the mean percent error decreased. This is probably related to numerical roundoff errors in the calculated mass of propellant burnt for the smaller time steps. Similar examinations using the other form functions showed little or no dependence of the percent error on the number of data points utilized. Ultimately, this indicates that the method should be reasonably reliable when using a small number of manually entered pressure points to compute burn rates.

Experimental Impetus

It was not practical to validate experimental impetus calculations via test firings. It was possible, however, to verify the calculation by comparison with results from the BLAKE thermodynamic code. BLAKE computes pressure, impetus, co-volume, molecular weight, and other thermodynamic properties of propellant combustion products at various loading densities. In essence, the pressure from a BLAKE computation at a given loading density is the equivalent of the maximum pressure from an adiabatic closed bomb test. Under the circumstances, the experimental impetus computed by the proposed method should be the same as the theoretical impetus from BLAKE.

The propellant composition chosen for the evaluation was a ball propellant, X-4179, manufactured by the Olin Corporation. The composition of X-4179 is given in Figure 8. The input to BLAKE is given in Figure 9 and the output from BLAKE appears in Figure 10.

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Olin

To Whom It May Concern:

Shown below are the analytical results on the following unrolled propellants:

	X-4179	X-4180	X-4182	X-4183
Coating Series No.	340-104	223-33	418-143	208-193
Ave. Grain Diameter	.0284"	.0238"	.0271"	.0163"
Nitrogen of NC, %	13.16	13.02	13.04	13.16
Nitrocellulose, %	59.94	65.27	75.17	85.95
Nitroglycerin, %	37.86	32.54	22.77	11.91
Dibutylphthalate, %	0.28	0.25	0.24	0.37
Diphenylamine, %	0.49	0.84	0.84	0.77
N-Nitroso Diphenylamine, %	0.81	0.53	0.53	0.54
Dinitrotolvene, %	0.14	0.14	0.08	0.07
Water, %	0.46	0.39	0.44	0.77
Moisture and Volatiles, %	0.52	0.43	0.51	0.94
Total Volatiles, %	0.51	0.42	0.50	1.01
Residual Solvent, %	0.04	0.03	0.06	0.24
Ethyl Acetate, %	0.00	0.00	0.03	0.22
Benzene, %	0.04	0.03	0.03	0.02
Sodium Sulfate, %	0.09	0.09	0.08	0.09
Calcium Carbonate, %	0.04	0.04	0.03	0.02
Ash, %	0.15	0.13	0.09	0.17
Graphite, %	0.20	0.17	0.17	0.11
Dust, %	0.03	0.04	0.00	0.00
120° Stability, SP Time, Min.	55	70	80	115

D. P. Zaidan
Manager, Technical Services
Powder Operation

DZ6.014.2

Figure 8. Composition of X-4179, Olin Corporation

THE COMPOSITION IS

NAME	PCT WT	PCT MOLE	DEL H-CAL/M	FORMULA
NC1316	58.986	.087	-1.6457E+08	$C_{6000} H_{7361} O_{10278} N_{2639}$
NG	37.258	67.996	-8.8600E+04	$C_3 H_5 O_9 N_3$
DBP	.276	.411	-2.0140E+05	$C_{16} H_{22} O_4$
DPA	.483	1.182	3.1070E+04	$C_{12} N_1 H_{11}$
SLOP	.789	1.649	5.0930E+04	$C_{12} H_{10} N_2 O_1$
DNT	.138	.314	-1.7100E+04	$C_7 H_6 O_4 N_2$
H2O	.460	10.576	-6.8315E+04	$H_2 O_1$
ETOH	1.069	9.620	-6.6420E+04	$C_2 H_6 O_1$
C6H6	.039	.207	1.1720E+04	$C_6 H_6$
SODSU	.089	.260	-2.6920E+05	$NA_2 S_1 O_4$
CALC	.217	.907	-2.8851E+05	$K_1 C_1 O_3$
C	.197	6.793	0.	C_1

THE HEAT OF FORMATION IS -530.95 CAL/GRAM = -2.2005E+05 CAL/MOLE.

THE ELEMENTS AND PERCENT BY MOLE
C	20.577
H	28.426
O	39.626
N	11.327
NA	.013
S	.007
K	.023

Figure 9. Composition for X-4179 used in BLAKE

	RHO/L G/CC	TEMP K	PRESSURE PSI	IMPETUS FT-LB/LB	MOL WT GAS	CO-VOL CU IN	FROZEN GAMMA	CP(FR) CAL/M-K	B(T) CU IN	C(T) IN**6	GAS VOL CU IN/LB	S GIDBS	H CAL/G	E CAL/G	ADEXP	PHI
1)	.0500	3586.	8743.	382646.	26.069	28.38	1.2145	11.30	1.652	2.19	553.598	2.29	-242.8	-531.0	1.2399	1.0540
2)	.1000	3635.	18626.	386443.	26.162	27.83	1.2139	11.39	1.650	2.19	276.799	2.23	-224.0	-530.9	1.3141	1.1118
3)	.1500	3661.	29647.	388500.	26.214	27.28	1.2144	11.45	1.648	2.19	184.533	2.20	-205.2	-531.0	1.3871	1.1735
4)	.2000	3680.	41898.	389901.	26.250	26.73	1.2155	11.52	1.647	2.19	138.399	2.17	-185.7	-531.0	1.4601	1.2393
5)	.2500	3693.	55479.	390964.	26.277	26.15	1.2172	11.58	1.647	2.19	110.720	2.15	-165.3	-531.0	1.5331	1.3093
6)	.3000	3704.	70494.	391913.	26.299	25.57	1.2196	11.64	1.646	2.19	92.266	2.14	-143.7	-531.0	1.6059	1.3833
7)	.3500	3714.	87047.	392515.	26.317	24.97	1.2225	11.71	1.645	2.19	79.085	2.12	-121.1	-531.0	1.6782	1.4615
8)	.4000	3722.	105257.	393113.	26.333	24.38	1.2260	11.78	1.645	2.19	69.195	2.11	-97.4	-531.0	1.7498	1.5439
9)	.4500	3729.	123206.	393627.	26.348	23.78	1.2299	11.85	1.644	2.19	61.508	2.10	-72.5	-531.0	1.8205	1.6304
10)	.5000	3735.	147014.	394073.	26.361	23.19	1.2344	11.93	1.644	2.19	55.358	2.09	-46.4	-531.0	1.8903	1.7210
11)	.5500	3740.	170787.	394462.	26.374	22.61	1.2393	12.02	1.644	2.19	50.326	2.08	-19.3	-531.0	1.9590	1.8158
12)	.6000	3745.	196631.	394803.	26.386	22.04	1.2446	12.10	1.643	2.19	46.132	2.08	9.1	-531.0	2.0266	1.9147
13)	.6500	3750.	224651.	395100.	26.399	21.48	1.2504	12.19	1.643	2.18	42.584	2.07	38.6	-531.0	2.0931	2.0177
14)	.7000	3754.	254952.	395357.	26.411	20.93	1.2565	12.29	1.643	2.18	39.542	2.06	69.2	-531.0	2.1585	2.1250
15)	.7500	3758.	287639.	395578.	26.424	20.40	1.2630	12.39	1.643	2.18	36.906	2.06	101.0	-531.0	2.2228	2.2363
16)	.8000	3761.	322814.	395762.	26.437	19.89	1.2699	12.49	1.643	2.18	34.600	2.05	134.0	-531.0	2.2859	2.3518

Figure 10. <u>Results from BLAKE for X-4179</u>

Using the BLAKE results for a loading density of 0.25 g/cc with a bomb volume of 100 cc the weight of the igniter (assumed to have identical thermochemical properties to the propellant) is selected as 1 gm and that of the propellant 24 gm. Figure 11 shows the results of MINICB using the experimental impetus option for this propellant with input values for the necessary thermochemical values taken from BLAKE.

IMPETUS CALCULATION

IGNITER IMPETUS: 390964 FT-LB/LB

IGNITER CO-VOLUME: 26.15 CU IN/LB

IGNITER WEIGHT: .002205 LB

PROPELLANT WEIGHT: .05292 LB

PROPELLANT CO-VOLUME: 26.15 CU IN/LB

BOMB VOLUME: 100 CC

MAXIMUM PRESSURE: 55479 PSI

IMPETUS= 1163.414 J/G

IMPETUS= 390895 FT-LB/LB

Figure 11. Experimental Impetus results from
            MINICB for X-4179

From Figure 10 the theoretical impetus for a loading density of 0.25 g/cc
is 390964 Ft-lb/lb. MINICB calculates a impetus of 390895 Ft-lb/lb which
represents a percent error of -0.0176%. This small difference is probably a
result of round-off errors. Considering the purpose of the computations, which
is to compute experimental impetus as a practical performance index, the
agreement is reasonable.

V. SUMMARY

MINICB, with overall error limits of at most 1.5%, can be a particularly
useful tool in the computation of burning rates or experimental impetus from

closed bomb pressure-time curves. This is especially true in situations where only a limited number of pressure-time data points are available, the propellant has an unusual grain geometry, or is a new formulation and feedback is quickly needed for the experimental program to proceed. Considering the minimal environment necessary for running MINICB and the simplicity of use, it is felt that MINICB meets the stated objects set out in the introduction.

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TABLE OF SYMBOLS

A	Instantaneous propellant surface area
b	Co-volume correction term
C	Weight of the Propellant
C_p	Weight of Propellant Burnt
C_{is}	Weight of the Igniter
C_i	Weight of Igniter Burnt
d	Perf diameter
D	Propellant outer diameter
F_p	Experimental Impetus of propellant
F_i	Theoretical impetus of Igniter
L	Grain length
m_p	Average molecular weight of Propellant combustion products
m_i	Average molecular weight of Igniter combustion products
$\sim$	Number of moles of gas
	Number of moles of igniter gas products
N_p	Number of moles of propellant gas products
n_p	Co-volume of the Propellant Combustion products
n_i	Co-volume of the Igniter Combustion products
Pmax	Observed maximum pressure
Ptheo	Theoretical maximum pressure

TABLE OF SYMBOLS (Con't)

Pi	Mathematical pi
P_p, P	Density of the Propellant
P_i	Solid igniter density
P	Chamber Pressure
R	Universal Gas Constant
r	Burn rate
T	System gas temperature
T_p	Flame Temperature of the Propellant
T_i	Flame Temperature of the Igniter
x	Linear distance burnt
V	Volume of empty chamber
V_b	Free Volume in the bomb

APPENDIX A

SURFACE AREA FORMULAS

I. Cord Burning Cigarette Fashion: An example of this type of burning grain is shown in Figure A-1.
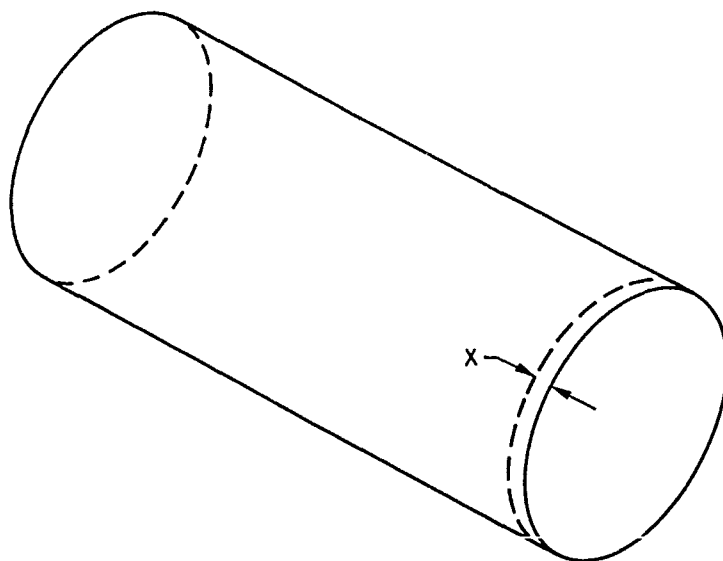
Figure A-1. A cord burning in a cigarette fashion.

For this particular grain geometry the burning is all on one end and the surface area of the burning surface remains constant and is given by equation (A-1).

$$A = (Pi/4)*D^2 \qquad\qquad (A-1)$$

II. Single Perf Burning Only on Perf Surface: A diagram of the way in which the grain is burning is shown in Figure A-2.
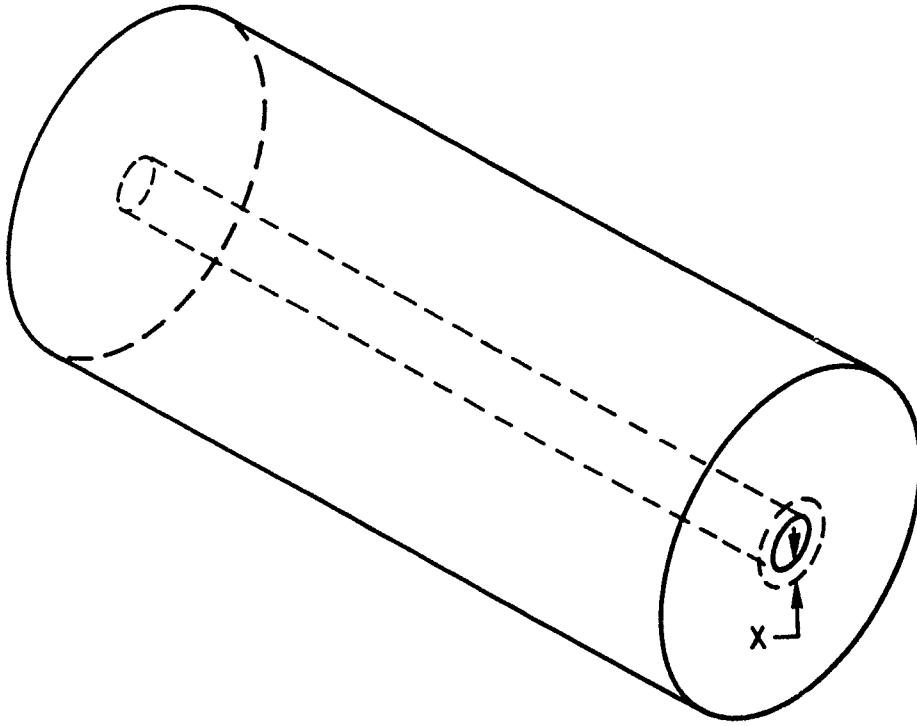
Figure A-2. **A single perf grain burning only on the perf surface.**

The equation for the volume burnt is given in equation (A-2).

$$\text{Volume Used} = L*Pi*[((d + 2x)/2)^2 - (d/2)^2] \qquad \text{(A-2)}$$

Squaring and simplifying in the brackets yields

$$\text{Volume Used} = L*Pi*[dx + x^2] \qquad \text{(A-3)}$$

Thus, multiplying by the density, which is denoted by p instead of p_p, to obtain the total propellant burnt, equation(A-4) is obtained.

$$C_p = p*L*Pi*[dx + x^2] \qquad (A-4)$$

Rearranging, the following quadratic equation in x is obtained.

$$x^2 + dx - C_p/(p*Pi*L) = 0 \qquad (A-5)$$

Letting $B = C_p/(p*Pi*L)$ and using the quadratic formula to solve for x.

$$x = \frac{-d +- \sqrt{d^2 + 4*B}}{2} \qquad (A-6)$$

Since x is positive the positive root is chosen in the expression for x. Next the equation for the surface area for this grain is

$$A = L*Pi*[d + 2x] \qquad (A-7)$$

Substituting (A-6) into (A-7) yields the final expression for the surface area

$$A = L*Pi*\sqrt{[d^2 + 4*C_p/(L*Pi*p)]} \qquad (A-8)$$

III. Single Perf Burning on Ends and Perf Surface: A diagram of this grain is shown in Figure A-3.
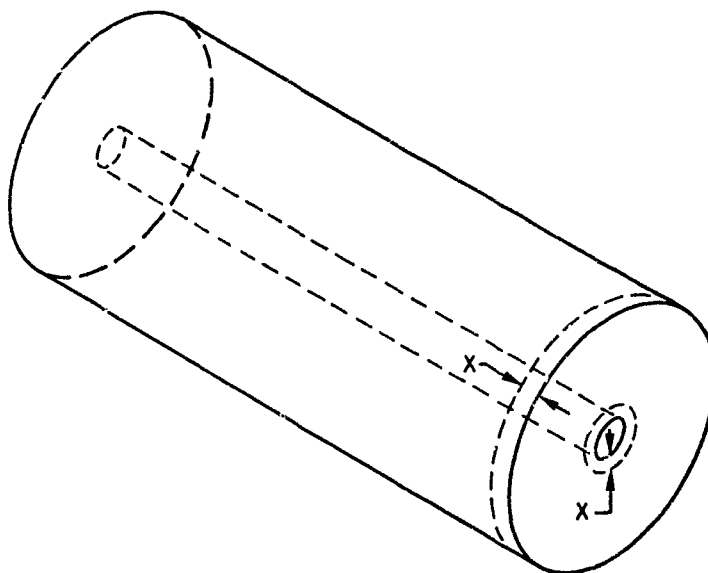
Figure A-3. Single perf burning on ends
and perf surface.

Again start with an expression for the total volume used.

$$\text{Volume Used} = L*Pi*[((d + 2x)/2)^2 - (d/2)^2]$$

$$+ 2x*Pi*[(D/2)^2 - ((d + 2x)/2)^2] \qquad (A-9)$$

In equation (A-9) the first term represents the volume burnt from inside the perf and the second term that burnt off both ends which was not accounted for in the first term. Simplifying and multiplying by density to obtain the total propellant burnt equation (A-10) is obtained.

$$C_p = (Pi*p/2)*[2*L*d*x + 2*L*x^2 + xD^2$$

$$- xd^2 - 4*d*x^2 - 4*x^3]$$

<div align="right">(A-10)</div>

Rearranging to obtain an equation in terms of x,

$$x^3 + (-L/2 + d)*x^2 + (-L*d/2 - D^2/4 + d^2/4)*x$$

$$+ C_p/(2*Pi*p) = 0$$

<div align="right">(A-11)</div>

Now this is a cubic equation in x and the tendency is to assume that there is one real root and two complex roots. However, this is not the case. To see this, note that the intercept is positive and that the lead coefficient also positive. Thus, if a graph was made of this function it would tend to positive infinity as x went to positive infinity and would be positive for x equal to zero, see Figure A-4. Therefore, the graph must cross the positive x-axis twice or not at all. However, if it does not cross the positive x-axis then no solution would exist, but one must exist. Hence, equation (A-11) has three real roots, two positive and one negative.

F(X)
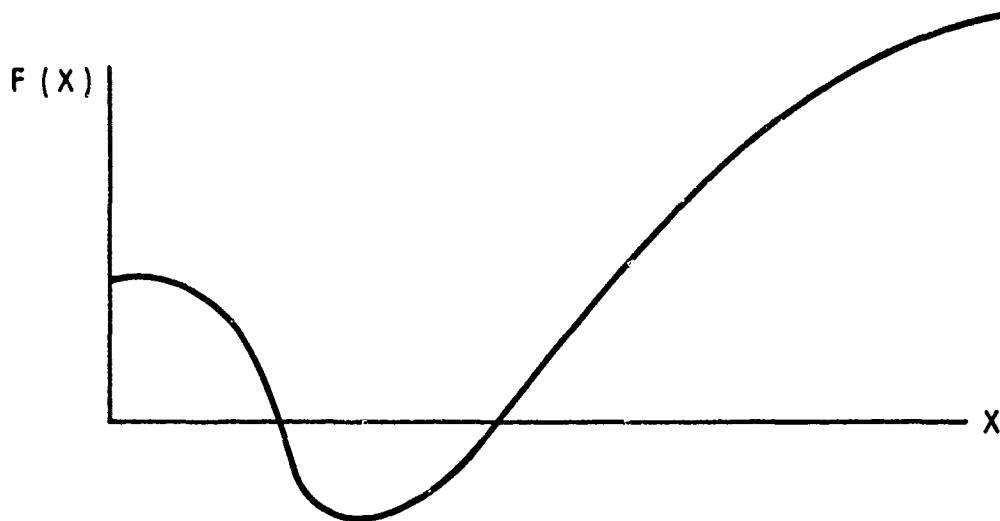
[graph]

Figure A-4.   Graph of the Equation Defined
             by Equation (A-11)

After analyzing solutions of cubic equations it became obvious that a
numerical solution for equation (A-11) was the only feasible method for
solving for x and keeping to the objective of having a simple and easy to run
program. The Newton Iterative method, starting with an initial guess of 0,
for finding roots has proven sufficient in computing the root.

Having obtained a value for x, the surface area is given by equation (A-12).

$$A = Pi*[d + 2x] + 2*Pi*[(D/2)^2 - ((d + 2x)/2)^2]$$ (A-12)

IV. N-th Perf Grain: An example of this grain geometry for seven perfs is shown in Figure A-5.
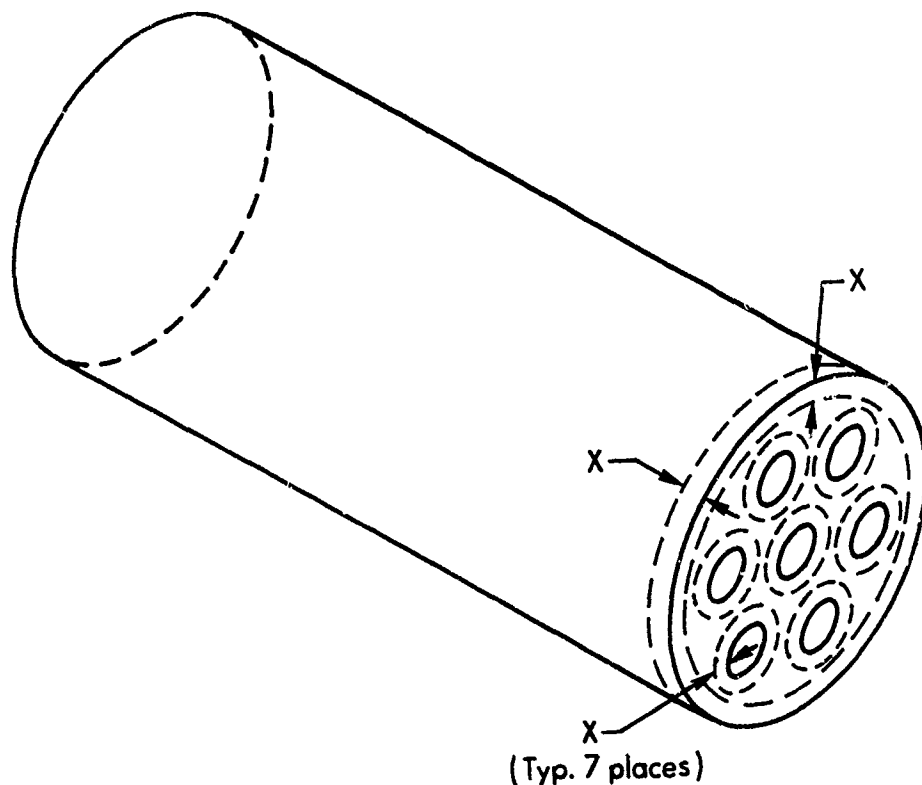
Figure A-5. S<u>even Perf Grain</u>

In the following derivation for the surface area the analysis is only correct up to the point of slivering and assumes that the webs are equal and that all perf diameters are the same. A equations will be derived for n perfs not just the seven shown in Figure A-5. Also, this analysis will not be valid for a single perf grain. As before, the starting point is the volume used and is given in equation (A-13) which is very similar to that for a single perf grain.

$$\text{Volume Used} = L*Pi*[(D/2)^2 - 2x)/2)^2]$$

$$+ n*L*Pi*[((d + 2x)/2)^2 - (d/2)^2]$$

$$+ 2x*Pi*[((D - 2x)/2)^2 - n*((d + 2x)/2)^2] \qquad (A-13)$$

Multiplying by density to obtain the total amount of propellant burnt and rearranging to obtain an equation in x, equation (A-14) is obtained.

$$(4n - 4)x^3 + (4D + 4nd - 2Ln + 2L)x^2$$

$$+ (nd^2 - D^2 - 2Ldn - 2LD)x + 2C_p/(Pi*p) = 0 \qquad (A-14)$$

As in III. the cubic also has three real roots and a numerical method should be used to determine the value of x. Having determined x the surface area is given by equation (A-15).

$$A = (Pi/2)*[(D - 2x)^2 - n(d + 2x)^2]$$

$$+ Pi*(L - 2x)*[n*(d + 2x) + (D - 2x)] \qquad (A-15)$$

APPENDIX B

PROGRAM LISTING FOR MINICB

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```
10 REM date of version: 17 december 1986
100 WIDTH "LPT1:",80:OPEN "LPT1:" FOR OUTPUT AS #3
110 DIM R(1028,9)
120 COLOR 14
130 REM mini closed bomb program written by william oberle
140 REM ** main menu and selection of options **
150 REM *************************************************
160 CLS:PRINT :PRINT :PRINT :PRINT :PRINT :PRINT :PRINT
170 PRINT "        Mini Closed Bomb Program"
180 PRINT "              OPTIONS"
190 PRINT
200 PRINT "    1. Perform impetus calculations"
210 PRINT "    2. Reduce pressure/time data to burning rates"
220 PRINT "    3. End this program"
230 PRINT :PRINT
240 INPUT "Select option by number";O
250 IF O=3 THEN END
260 IF (O<>1 AND O<>2) THEN BEEP:PRINT "Not a selection":GOTO 240
270 GOSUB 290:IF O=1 THEN GOSUB 740 ELSE GOSUB 930
280 GOTO 160
290 REM ** subroutine to enter needed information for options 1 and 2 **
300 REM ***************************************************************
310 FI=0:CLS:PRINT :PRINT :PRINT :PRINT :PRINT :PRINT
320 PRINT "Certain information is needed to perform the selected option."
330 PRINT "You will be asked for this information, please be sure to enter"
340 PRINT "the information with the correct units. DO NOT HIT RETURN!!"
350 FOR KK=1 TO 8000:NEXT KK
360 CLS
370 PRINT :PRINT :PRINT :PRINT :PRINT :PRINT :PRINT
380 PRINT "    IGNITER INFORMATION"
390 PRINT :PRINT "IF THE VALUE OF THE IMPETUS OF THE IGNITER IS KNOWN,ENTER ITS"
400 PRINT "VALUE IN FT.-LB./LB. IF BLACK POWDER IS BEING USED ENTER  -1,"
410 PRINT "OTHERWISE HIT RETURN."
420 INPUT FI:FI=FI*12
430 IF FI=-12 THEN FI=975001:TI=2170:FI=FI*12:MI=33.64:NI=21.8:GOTO 500
440 IF (O=1 AND FI<>0) THEN 490
450 INPUT "ENTER THE FLAME TEMPERATURE OF THE IGNITER(K)",TI
460 INPUT "ENTER THE MOLECULAR WEIGHT OF THE IGNITER";MI
470 IF FI<>0 THEN 490
480 FI=8.31433*TI/MI/.0029390706#:FI=FI*12
490 INPUT "ENTER THE CO-VOLUME(CU IN./LB) OF THE IGNITER";NI
500 INPUT "ENTER THE WEIGHT(LB) OF THE IGNITER";CI
510 CLS
520 PRINT :PRINT :PRINT :PRINT :PRINT :PRINT
530 PRINT "    PROPELLANT DATA"
```

```
540 INPUT "ENTER THE WEIGHT(LB) OF THE PROPELLANT";CP
550 INPUT "ENTER THE CO-VOLUME(CU IN/LB) OF THE PROPELLANT";NP
560 IF O=1 THEN 680
570 INPUT "ENTER THE FLAME TEMPERATURE(K) OF THE PROPELLANT";TP
580 INPUT "ENTER THE MOLECULAR WEIGHT OF THE PROPELLANT";MP
590 INPUT "ENTER THE DENSITY OF THE PROPELLANT(LB/CU IN)";RHO
600 CLS
610 PRINT :PRINT :PRINT :PRINT :PRINT :PRINT :PRINT
620 PRINT "    GRAIN INFORMATION"
630 INPUT "ENTER THE GRAIN DIAMETER(IN)";D
640 INPUT "ENTER THE GRAIN LENGTH(IN)";L
650 INPUT "ENTER THE NUMBER OF PERFS";NNP
660 INPUT "ENTER THE AVERAGE PERF DIAMETER(IN)";PD
670 INPUT "ENTER THE OUTER, MIDDLE, AND INNER WEB(IN)";WO,WM,WI
680 CLS
690 PRINT :PRINT :PRINT :PRINT :PRINT :PRINT :PRINT
700  PRINT "    BOMB AND PRESSURE INFORMATION"
710 INPUT "ENTER THE OBSERVED PMAX(PSI)";PMAX
720 INPUT "ENTER THE BOMB VOLUME(CC)";VB
730 RETURN
740 REM ** IMPETUS CALCULATIONS **
750 REM ****************************************************************
760 LPRINT " IMPETUS CALCULATION"
770 LPRINT :LPRINT :
780 LPRINT "IGNITER IMPETUS:        ";FI/12;" FT-LB/LB"
790 LPRINT "IGNITER CO-VOLUME:      ";NI;" CU IN/LB"
800 LPRINT "IGNITER WEIGHT:         ";CI;" LB"
810 LPRINT
820 LPRINT "PROPELLANT WEIGHT:      ";CP;" LB"
830 LPRINT "PROPELLANT CO-VOLUME: ";NP;" CU IN/LB"
840 LPRINT
850 LPRINT "BOMB VOLUME:            ";VB;" CC"
860 LPRINT "MAXIMUM PRESSURE:       ";PMAX;" PSI"
870 LPRINT :LPRINT
880 FI=FI/12
890 FP=((PMAX/145.038)*(VB-CP*16.387045#*NP-CI*16.387045#*NI)
        -FI*.0029890706#*CI*453.592)/(CP*453.592)
900 LPRINT "IMPETUS=";FP;" J/G"
910 LPRINT "IMPETUS=";INT(FP/.0029890706#);" FT-LB/LB"
920 RETURN
930 REM ** BURNING RATE ANALYSIS **
940 REM ****************************************************************
950 PTHEO=(33372!*TP*CP/MP+FI*CI)/(VB/16.38706-CP*NP-CI*NI)
960 TOS=(CP*TP+CI*TI)/(CP+CI)
970 TS=TOS*PMAX/PTHEO
980 CON1=VB/16.38706-CP/RHO-CI*NI
990 CON2=CI*FI*TS/TI
1000 CON3=33372!*TS/MP
1010 CON4=NP-1/RHO
1020 PIG=FI*TS*CI/TI/(VB/16.38706-CP/RHO-CI*NI)
```

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```
1030 CLS:PRINT :PRINT :PRINT :PRINT :PRINT :PRINT
1040 PRINT "THIS PROGRAM ASSUMES THAT THE IGNITER IS ALL BURNT BEFORE THE "
1050 PRINT "PROPELLANT STARTS TO BURN. THUS, THE POINTS TO BE ENTERED IN"
1060 PRINT "THE PRESSURE VS TIME TABLE MUST START WITH A PRESSURE GREATER"
1070 PRINT "THAN THE PRESSURE DUE TO THE IGNITER.  THIS PRESSURE IS ";PIG;"
     PSI"
1080 PRINT :PRINT
1090 PRINT "THE PROGRAM ALSO ASSUMES THAT THE TIME STEP IS A CONSTANT."
1100 INPUT "PLEASE ENTER THIS CONSTANT TIME STEP(MSEC)";DT:DT=DT/1000
1110 INPUT "ENTER THE STARTING TIME(MSEC)";TSTART:TSTART=TSTART/1000
1120 CLS
1130 PRINT :PRINT:PRINT :PRINT :PRINT :PRINT
1140 PRINT "THIS PROGRAM WILL SUPPORT THE FOLLOWING FORM FUNCTIONS."
1150 PRINT :PRINT :
1160 PRINT "      1.   CIGARETTE"
1170 PRINT "      2.   INHIBITED SINGLE PERF(BURNS ONLY ON PERF SURFACE)"
1180 PRINT "      3.   SINGLE PERF"
1190 PRINT "      4.   MULTI-PERF"
1200 PRINT "      5.   SINGLE PERF INHIBITED ON LATERAL OUTER SURFACE"
1210 PRINT :PRINT
1220 INPUT "ENTER YOUR CHOICE FOR THE FORM FUNCTION BY NUMBER";FFO
1230 CLS:PRINT :PRINT :PRINT :PRINT :PRINT :PRINT
1240 PRINT "THE PRESSURE DATA MAY BE ENTERED FROM A DATA FILE OR BY HAND."
1250 PRINT "IF A DATA FILE IS TO BE USED THE LAST PRESSURE MUST BE -1."
1260 PRINT "THE FILE IS TO CONTAIN PRESSURE VALUES ONLY."
1270 PRINT :PRINT :INPUT "ENTER F FOR FILE INPUT OR H FOR HAND INPUT";Z$
1280 IF Z$="H" THEN 1400
1290 IF Z$<>"F" THEN PRINT "NOT A CHOICE":GOTO 1240
1300 PRINT:PRINT
1310 PRINT "ENTER THE NAME OF THE FILE CONTAINING THE PRESSURE DATA."
1320 PRINT "BE SURE TO INCLUDE THE DRIVE SPECIFICATION IF IT IS NOT C."
1330 INPUT "THE FILE NAME IS";FP$
1340 OPEN FP$ FOR INPUT AS #1
1350 N=1:R(0,1)=TSTART-DT
1360 INPUT #1,R(N,2)
1370 IF R(N,2)=-1 THEN CLOSE #1:GOTO 1490
1380 R(N,1)=R(N-1,1)+DT
1390 N=N+1:GOTO 1360
1400 PRINT "ENTER THE PRESSURE DATA IN PSI, TERMINATE INPUT WITH A NEGATIVE"
1410 PRINT "VALUE FOR THE PRESSURE."
1420 PRINT :PRINT
1430 N=1:R(0,1)=TSTART-DT
1440 PRINT "ENTER THE PRESSURE FOR POINT NUMBER ";N
1450 INPUT R(N,2)
1460 IF R(N,2)<0 THEN 1490
1470 R(N,1)=R(N-1,1)+DT
1480 N=N+1:GOTO 1440
1490 N=N-1
1500 LPRINT CHR$(12)
1510 LPRINT "                    HIGH PRESSURE COMBUSTION RESEARCH TEAM"
```

```
1520 LPRINT "                    BALLISTIC RESEARCH LABORATORY"
1530 LPRINT "              INTERIOR BALLISTICS DIVISION - ABC BRANCH"
1540 LPRINT "              MINI CLOSED BOMB INFORMATION AND RESULTS"
1550 LPRINT:LPRINT
1560 LPRINT TAB(40);"IGNITER";TAB(60);"PROPELLANT"
1570 LPRINT "IN  RTUS(FT-LB/LB):";TAB(37);
1580 LPRINT USI  "######.#####";FI/12::LPRINT TAB(60);"NOT COMPUTED"
1590 LPRINT "FLAME TEMP.(K):";TAB(37);
1600 LPRINT USING "######.#####";TI;:LPRINT TAB(57);
     :LPRINT USING "######.#####";TP
1610 LPRINT "MOLECULAR WEIGHT:";TAB(37);
1620 LPRINT USING "######.#####";MI;:LPRINT TAB(57);
     :LPRINT USING "######.#####";MP
1630 LPRINT "CO-VOLUME(INCH^3/LB):";TAB(37);
1640 LPRINT USING "######.#####";NI;:LPRINT TAB(57);
     :LPRINT USING "######.#####";NP
1650 LPRINT "WEIGHT:";TAB(37);
1660 LPRINT USING "######.#####";CI;:LPRINT TAB(57);
     :LPRINT USING "######.#####";CP
1670 LPRINT "DENSITY(LB/INCH^3):";TAB(37);"NOT COMPUTED";TAB(57);
1680 LPRINT USING "######.#####";RHO
1690 LPRINT:LPRINT
1700 LPRINT TAB(20);"GRAIN INFORMATION(INCHES)"
1710 LPRINT "DIAMETER:";TAB(18);
1720 LPRINT USING "######.#####";D
1730 LPRINT "LENGTH:";TAB(18);
1740 LPRINT USING "######.#####";L
1750 LPRINT "NUMBER OF PERFS";TAB(18);
1760 LPRINT USING "######.#####";NNP
1770 LPRINT "AVG. PERF DIAM:";TAB(18);
1780 LPRINT USING "######.#####";PD
1790 LPRINT "OUTER WEB:";TAB(18);
1800 LPRINT USING "######.#####";WO
1810 LPRINT "MIDDLE WEB:";TAB(18);
1820 LPRINT USING "######.#####";WM
1830 LPRINT "INNER WEB:";TAB(18);
1840 LPRINT USING "######.#####";WI
1850 LPRINT "FORM FUNCTION:";TAB(18);
1860 LPRINT USING "######.#####";FFO
1870 LPRINT:LPRINT
1880 LPRINT TAB(20);"BOMB AND PRESSURE INFORMATION"
1890 LPRINT "BOMB VOLUME(CC):",TAB(22);
1900 LPRINT USING "######.#####";VB
1910 LPRINT "OBSERVED PMAX(PSI):";TAB(22);
1920 LPRINT USING "######.#####";PMAX
1930 LPRINT "THEO. PMAX(PSI):";TAB(22);
1940 LPRINT USING "######.#####";PTHEO
1950 REM ** SMOOTHING PRESSURE DATA SO THE PRESSURE
            IS ALWAYS INCREASING **
1960 REM ***************************************************
```

```
1970 FOR I=1 TO N-1
1980 IF R(I,2)<=R(I+1,2) THEN 2010
1990 IF I=N-1 THEN R(I+1,2)=R(I,2):GOTO 2010
2000 IF R(I,2)<= R(I+2,2) THEN R(I+1,2)=(R(I,2)+R(I+2,2))/2 ELSE
     R(I,2)=(R(I-1,2)+R(I+1,2))/2
2010 NEXT I
2020 REM ** COMPUTATION OF PROPELLANT BURNT AT EACH TIME STEP **
2030 REM ***************************************************************
2040 FOR I=1 TO N
2050 R(I,4)=(R(I,2)*CON1-CON2)/(CON3+R(I,2)*CON4)
2060 NEXT
2070 CLS:PRINT :PRINT :PRINT :PRINT
2080 PRINT "DO YOU WANT A FIVE POINT SMOOTHING BRIDGE FOR dP/dt AND dM/dt?"
2090 INPUT "ANSWER Y OR N";T$
2100 IF T$<>"Y" THEN 2240
2110 REM ** COMPUTING DP/DT AND DC/DT USING A FIVE POINT BRIDGE **
2120 REM **********************************************************
2130 DEF FNF(1)=(-2*R(I-2,Q1)-R(I-1,Q1)+R(I+1,Q1)+2*R(I+2,Q1))/(10*DT)
2140 FOR Q1=2 TO 4 STEP 2
2150 FOR I=3 TO N-2
2160 R(I,Q1+1)=FNF(I)
2170 NEXT I
2180 NEXT Q1
2190 R(2,3)=(R(2,2)-R(1,2))/DT:R(N-1,3)=(R(N-1,2)-R(N-2,2))/DT
2200 R(N,3)=(R(N,2)-R(N-1,2))/DT:R(2,5)=(R(2,4)-R(1,4))/DT
2210 R(N-1,5)=(R(N-1,4)-R(N-2,4))/DT:R(N,5)=(R(N,4)-R(N-1,4))/DT
2220 INPUT "ANOTHER SMOOTHING PASS?";Z$:IF Z$="Y" THEN 2140
2230 GOTO 2280
2240 FOR I=2 TO N
2250 R(I,3)=(R(I,2)-R(I-1,2))/DT
2260 R(I,5)=(R(I,4)-R(I-1,4))/DT
2270 NEXT I
2280 REM ** COMPUTATION OF SURFACE AREA BASED ON FORM FUNCTION **
2290 REM ***************************************************************
2300 IF FFO=1 THEN AREA=ATN(1)*D*D:FOR I=1 TO N:R(I,9)=AREA:NEXT I
2310 IF FFO=1 THEN NOG=CP/(AREA*L*RHO):GOTO 2360
2320 IF FFO=2 THEN GOSUB 2860
2330 IF FFO=3 THEN GOSUB 2960
2340 IF FFO=4 THEN GOSUB 3070
2350 IF FFO=5 THEN GOSUB 3260
2360 REM ** FINDING AVERAGE TIME AND PRESSURE VALUES **
2370 REM ***************************************************************
2380 FOR I=2 TO N
2390 R(I,7)=((R(I,1)+R(I-1,1))/2)*1000
2400 R(I,8)=(R(I,2)+R(I-1,2))/2
2410 NEXT
2420 REM ** COMPUTATION OF BURNING RATE **
2430 FOR I=2 TO N
2440 R(I,6)=R(I,5)/R(I,9)/RHO/NOG
2450 NEXT I
```

```
2460 CLS:PRINT :PRINT :PRINT :PRINT
2470 PRINT "ENTER A NAME FOR THE OUTPUT FILE."
2480 INPUT "DO NOT INCLUDE A DRIVE, DATA WILL BE SAVED ON THE A DRIVE";N$
2490 OPEN "A:"+N$ FOR OUTPUT AS #2
2500 CLS:LPRINT "NUMBER OF GRAINS    ",NOG:LPRINT CHR$(12)
2510 PRINT "TIME","PRESSURE","DP/DT"," %","R","SURF. A"
2520 PRINT #2,"TIME","PRESSURE","DP/DT"," %","R","SURF. A"
2530 PRINT "MSEC","PSI","PSI/SEC","BURNT","IN/SEC","FRAC."
2540 PRINT #2,"MSEC","PSI","PSI/SEC","BURNT","IN/SEC","FRAC."
2550 FOR I=2 TO N
2560 PER=INT((R(I,4)/CP)*10000)/100
2570 PRINT R(I,7),INT(R(I,8)),R(I,3),PER,R(I,6),R(I,9)/R(1,9)
2580 PRINT #2,R(I,7),INT(R(I,8)),R(I,3),PER,R(I,6),R(I,9)/R(1,9)
2590 NEXT I
2600 PRINT #2,CHR$(12):CLS
2610 PRINT "WOULD YOU LIKE A TABLE OF PRESSURE VS RATE STARTING AT THE ";
2620 PRINT INT(R(2,8)/1000)*1000+1000;" PSI INCREMENTED BY 500 PSI?"
2630 INPUT "ENTER Y OR N";A$
2640 IF A$="N" THEN 2850
2650 PRINT :PRINT :PRINT
2660 LPRINT "PRESSURE","RATE"
2670 PRINT #2,"PRESSURE","RATE"
2680 LPRINT "PSI","IN/SEC"
2690 PRINT #2,"PSI","IN/SEC"
2700 CON9=INT(R(2,8)/1000)*1000+1000
2710 CON10=INT(R(N,8)/1000)*1000
2720 CON11=R(N,8)-CON10
2730 IF CON11>=500 THEN CON12=CON10+500   ELSE CON12=CON10
2740 FOR I=CON9 TO CON12 STEP 500
2750 FOR J=2 TO N
2760 IF I<=R(J,8) THEN 2780
2770 NEXT J
2780 IF J=N THEN 2810
2790 RATE=((I-R(J-1,8))/(R(J,8)-R(J-1,8)))*(R(J,6)-R(J-1,6))+R(J-1,6)
2800 GOTO 2820
2810 RATE =R(N,6)
2820 LPRINT I,RATE
2830 PRINT #2,I,RATE
2840 NEXT I
2850 CLOSE #2:RETURN
2860 REM ** SUBROUTINE TO COMPUTF SURFACE AREA FOR SINGLE **
2870 REM ** PERF INHIBITED ON ALL SIDES EXCEPT THE PERF    **
2880 AREA=3.14159*PD*L
2890 VOL=3.14159*(D*D-PD*PD)*L/4
2900 NOG=CP/VOL/RHO
2910 FOR I=1 TO N
2920 TCZ=R(I,4)/NOG
2930 R(I,9)=L*3.14159*(PD*PD+4*TCZ/(L*RHO*3.14159))^.5
2940 NEXT I
2950 RETURN
```

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```
2960 REM SUBROUTINE FOR SINGLE PERF
2970 PI=4*ATN(1)
2980 VOL=PI*L/4*(D*D-PD*PD)
2990 NOG=CP/VOL/RHO
3000 FOR I=1 TO N
3010 TCZ=R(I,4)/NOG
3020 BB=(PD*PD-D*D-2*L*PD-2*L*D)
3030 TEMP=(-BB-SQR(BB*BB-4*(4*D+4*PD)*(2*TCZ/(RHO*PI))))/(8*(D+PD))
3040 R(I,9)=(PI/2)*((D-2*TEMP)^2-(PD+2*TEMP)^2)+PI*(L-2*TEMP)*(PD+D)
3050 NEXT I
3060 RETURN
3070 REM SUBROUTINE FOR N PERF WITH N<>1
3080 PI=4*ATN(1)
3090 VOL=PI*L/4*(D*D-NNP*PD*PD)
3100 NOC=CP/RHO/VOL
3110 FOR I=1 TO N
3120 TCZ=R(I,4)/NOG
3130 ALPHA=(L*NNP-L-2*D-2*NNP*PD)/(2-2*NNP)
3140 BETA=(D*D-NNP*PD*PD+2*NNP*L*PD+2*L*D)/(4-4*NNP)
3150 GAMMA=-TCZ/(RHO*PI*(2-2*NNP))
3160 TEMP1=0
3170 TEMP=TEMP1-(TEMP1^3+ALPHA*TEMP1^2+BETA*TEMP1+GAMMA)/
     (3*TEMP1^2+2*ALPHA*TEMP1+BETA)
3180 IF ABS(TEMP-TEMP1)<.000001 THEN 3200
3190 TEMP1=TEMP:PRINT TEMP:GOTO 3170
3200 PRINT "THE VALUE OF R IS ";TEMP
3210 GOTO 3230
3220 REM FINDING SURFACE AREA
3230 R(I,9)=(PI/2)*((D-2*TEMP)^2-NNP*(PD+2*TEMP)^2)+PI*(L-2*TEMP)
     *(NNP*(PD+2*TEMP)+(D-2*TEMP))
3240 NEXT I
3250 RETURN
3260 REM SUBROUTINE FOR SURFACE AREA OF INHIBITED SINGLE PERF
3270 REM WHERE INHIBITION IS ON OUTER LATERAL SURFACE ONLY
3280 PI=4*ATN(1)
3290 VOL=PI*L/4*(D*D-PD*PD)
3300 NOG=CP/VOL/RHO
3310 FOR I=1 TO N
3320 TCZ=R(I,4)/NOG
3330 ALPHA=(-L/2+PD)
3340 BETA=(-L*PD/2-D*D/4+PD*PD/4)
3350 GAMMA=TCZ/(RHO*PI*2)
3360 TEMP1=0
3370 TEMP=TEMP1-(TEMP1^3+ALPHA*TEMP1^2+BETA*TEMP1+GAMMA)
     /(3*TEMP1^2+2*ALPHA*TEMP1+BETA)
3380 IF ABS(TEMP-TEMP1)<.000001 THEN 3400
3390 TEMP1=TEMP:PRINT TEMP:GOTO 3370
3400 PRINT "THE VALUE OF R IS ";TEMP
3410 GOTO 3430
3420 REM FINDING SURFACE AREA
```

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```
3430 R(I,9)=PI*(PD+2*TEMP)*(L-2*TEMP)+(FI/2)*(D*D-(PD+2*TEMP)*(PD+2*TEMP))
3440 NEXT I
3450 RETURN
```

60

VARIABLE LIST

ALPHA	Temporary Storage
AREA	Initial Surface Area of One Grain
A$	Indicator For a TAble of Burning Rates by Pressure
BB	Temporary Storage
BETA	Temporary Storage
CI	Weight of Igniter
CP	Weight of Propellant
CON1	Stores a Constant
CON2	Stores a Constant
CON3	Stores a Constant
CON4	Stores a Constant
D	Grain Diameter
D	Time Increment
FFO	Form Function Indicator
FI	Theoretical Impetus of Igniter
FP	Experimental Impetus of Propellant
FP$	Input File Name
GAMMA	Temporary Storage
KK	Loop Index
L	Grain Length
MI	Molecular Weight of Igniter
MP	Molecular Weight of Propellant
N	Number of Data Points

VARIABLE LIST (Con't)

NI	Co-volume of Igniter
NNP	Number of Perfs
NOG	Number of Grains
NP	Co-volume of Propellant
N$	Name of Output File
O	Selected Option
PD	Average Perf Diameter
PI	Value of pi
PIG	Pressure Due to Igniter
PMAX	Observed Maximum Pressure
PTHEO	Theoretical Maximum Pressure
RHO	Propellant Density
R(-,-)	Array Used to Store Values R(-,1) -- Time R(-,2) -- Pressure R(-,3) -- dP/dt R(-,4) -- Total Mass of Propellant Burnt R(-,5) -- dC/dt, Mass Generation Rate R(-,6) -- Burn Rate R(-.7) -- Average Time R(-,8) -- Average Pressure R(-,9) -- Surface Area
TCZ	Total Mass Burnt From a Single Grain
TEMP	Temporary Storage
TEMP1	Temporary Storage
TI	Flame Temperature of Igniter

VARIABLE LIST (Con't)

TOS	Weighted Average of Flame Temperatures
TP	Flame Temperature of Propellant
TS	System Temperature
TSTART	Starting Time
T$	Indicator of Using Five Point Bridge
VB	Empty Bomb Volume
VOL	Initial Volume of a Single Grain
WI	Inner Web
WM	Middle Web
WO	Outer Web
Z$	Mode of Data Input

APPENDIX C

SAMPLE OUTPUT FROM MINICB

TABLE C-1. Example of output from MINICB using the
experimental impetus option.

IMPETUS CALCULATION

IGNITER IMPETUS: 390962 FT-LB/LB
IGNITER CO-VOLUME: 26.15 CU IN/LB
IGNITER WEIGHT: .002205 LB

PROPELLANT WEIGHT: .05292 LB
PROPELLANT CO-VOLUME: 26.15 CU IN/LB

BOMB VOLUME: 100 CC
MAXIMUM PRESSURE: 55479 PSI

IMPETUS= 1168.419 J/G
IMPETUS= 390896 FT-LB/LB

TABLE C-2. Example of disk file output from MINICB
with burning rate option chosen.

TIME	PRESSURE	DP/DT	%	R	SURF.
MSEC	PSI	PSI/SEC	BURNT	IN/SEC	FRAC.
.1	108	65000	.54	4.707604	1
.3	122	75000	.62	5.431525	1
.5	138	80000	.69	5.793249	1
.7000001	155	89999.99	.78	6.516937	1
.9000001	174	99999.99	.88	7.240458	1
1.1	195	110000	.98	7.9638	1
1.3	218	120000	1.1	8.686944	1
1.5	243	130000	1.22	9.40985	1
1.7	270	145000	1.36	10.49439	1
1.9	301	160000	1.52	11.57852	1
2.1	334	175000	1.69	12.66222	1
2.3	371	195000	1.88	14.10712	1
2.5	412	210000	2.08	15.1897	1
2.7	455	225000	2.3	16.27169	1
2.9	503	250000	2.54	18.07603	1
3.100001	555	270000	2.8	19.51781	1
3.300001	611	295000	3.08	21.31992	1
3.500001	673	325000	3.39	23.48195	1
3.700001	740	345000	3.73	24.91989	1
3.900001	813	380000	4.09	27.43963	1

TABLE C-2. Example of disk file output from MINICB
with burning rate option chosen. (Con't)

4.100001	892	410000	4.49	29.59606	1
4.300001	977	445000	4.92	32.11097	1
4.500002	1069	473000	5.37	34.26246	1
4.700001	1169	520000	5.87	37.49264	1
4.900002	1277	560000	6.41	40.35829	1
5.100000	1393	605000	6.99	43.58008	1
5.300002	1519	650000	7.61	46.79668	1
5.500002	1654	700000	8.29	50.36783	1
5.700002	1799	755000	9.01	54.29203	1
5.900002	1956	810000	9.79	58.20872	1
6.100003	2124	874999.9	10.62	62.83522	1
6.300002	2305	934999.9	11.52	67.09289	1
6.500003	2500	1010000	12.68	72.4153	1
6.700003	2708	1075000	13.51	77.0082	1
6.900003	2932	1160000	14.62	83.01926	1
7.100003	3171	1235000	15.8	88.29816	1
7.300004	3423	1330000	17 06	94.98603	1
7.500003	3703	1420000	18.41	101.2900	1
7.700004	3997	1520000	19.66	108.2989	1
7.900004	4311	1620000	21.39	115.2722	1
8.100003	4646	1735000	23.04	123.2818	
8.300003	5005	1855000	24.79	131.6106	1
8.500002	5388	1975000	26.66	139.9005	1
8.700002	5797	2115000	28.65	149.5617	1
8.900001	6234	2250000	30.77	158.8186	1
9.100001	6699	2400000	33.02	169.0787	1
9.300001	7195	2560000	35.42	179.9785	1
9.500001	7724	2730000	37.98	191.5081	1
9.700001	8287	2905000	40.69	203.3073	1
9.899999	8887	3095000	43.57	216.006	1
10.1	9526	3290000	46.62	229.0725	1
10.3	10206	3510000	49.87	243.703	1
10.5	10930	3730000	53.31	258.2045	1
10.7	11700	3970000	56.97	272.9456	1
10.9	12519	4225000	60.84	290.5591	1
11.1	13391	4495000	64.95	308.0206	1
11.3	14319	4780000	69 3	326.3053	1
11.5	15305	5085000	73.91001	345.726	1
11.7	16354	5405000	78.79	365.9094	1
11.9	17470	5750000	83.95	387.4975	1
12.1	18657	6120000	89.43	410.4453	1
12.3	19919	6505000	95.21	434.0344	1
12.5	21110	5400000	100	358.5719	1

TABLE C-2.   Example of disk file output from MINiCB
with burning rate option chosen   (Con't)

PRESSURE	RATE
PSI	IN/SEC
1000	32.63715
1500	46.30971
2000	59.41682
2500	72.4153
3000	84.51807
3500	96.6403
4000	108.3656
4500	119.7843
5000	131.483
5500	142.5343
6000	153.8562
6500	164.6878
7000	175.6933
7500	186.626
8000	197.2873
8500	207.826
9000	218.3577
9500	228.5429
10000	239.2708
10500	249.5917
11000	259.6353
11500	269.817
12000	280.0274
12500	290.1638
13000	300.1809
13500	310.1595
14000	320.0166
14500	329.8686
15000	339.7118
15500	349.4683
16000	359.0886
16500	368.7252
17000	378.4017
17500	388.0775
18000	397.7438
18500	407.41
19000	416.854
19500	426.1963
20000	358.5719
20500	358.5719
21000	358.5719

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TABLE C-3. Example of hardcopy output from MINICB
using burning rate option.

HIGH PRESSURE COMBUSTION RESEARCH TEAM
BALLISTIC RESEARCH LABORATORY
INTERIOR BALLISTICS DIVISION - ABC BRANCH
MINI CLOSED BOMB INFORMATION AND RESULTS

	IGNITER	PROPELLANT
IMPETUS(FT-LB/LB):	224583.30000	NOT COMPUTED
FLAME TEMP.(K):	2000.00000	3092.00000
MOLECULAR WEIGHT:	24.77100	24.77100
CO-VOLUME(INCH^3/LB):	30.00000	26.62000
WEIGHT:	0.00000	0.01650
DENSITY(LB/INCH^3):	NOT COMPUTED	0.05600

GRAIN INFORMATION(INCHES)

DIAMETER:	0.50000
LENGTH:	1.50000
NUMBER OF PERFS	0.00000
AVG. PERF DIAM.	0.00000
OUTER WEB:	0.00000
MIDDLE WEB:	0.00000
INNER WEB:	0.00000
FORM FUNCTION:	1.00000

BOMB AND PRESSURE INFORMATION

BOMB VOLUME(CC):	59.00000
OBSERVED PMAX(PSI):	21650.00000
THEO. PMAX(PSI):	21743.79000
NUMBER OF GRAINS	1.000367

PRESSURE	RATE
PSI	IN/SEC
1000	32.63715
1500	46.30971
2000	59.41682
2500	72.4153
3000	84.51807
3500	96.6403
4000	108.3636
4500	119.7843
5000	131.483

TABLE C-3. Example of hardcopy output from MINICB
using burning rate option. (Con't)

5500	142.5343
6000	153.8562
6500	164.6878
7000	175.6933
7500	186.626
8000	197.2873
8500	207.826
9000	218.3577
9500	228.5429
10000	239.2708
10500	249.5917
11000	259.6355
11500	269.857
12000	280.0274
12500	290.1638
13000	300.1809
13500	310.1595
14000	320.0166
14500	329.8686
15000	339.7118
15500	349.4683
16000	359.0886
16500	368.7252
17000	378.4017
17500	388.0775
18000	397.7438
18500	407.43
19000	416.854
19500	426.1963
20000	358.5719
20500	358.5719
21000	358.5719

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APPENDIX D

TRADITIONAL MEASUREMENT OF EXPERIMENTAL IMPETUS[6][9]

In this approach, heat loss and effects of the igniter are ignored. Problems with the igniter can be eliminated by having the igniter the same as the propellant. The following symbols will be used:

P	Pressure
V	Chamber Free Volume
F	Impetus
n	Co-volume
L	Loading Density
c	Charge Weight

Start with the Noble-Able equation of state,

$$P(V - nc) = Fc \qquad\qquad (D-1)$$

Divide by c,

$$P(V/c - n) = F \qquad\qquad (D-2)$$

Next divide by P to obtain

$$V/c - n = (1/P) F \qquad\qquad (D-3)$$

Since loading density is the charge weight divided by volume, $L = c/V$. Substituting into equation (D-3) gives

$$1/L = F(1/P) + n \tag{D-4}$$

Now by performing a series of closed bomb firings with different loading densities and recording the maximum observed pressure a plot of 1/L versus 1/P can be made. The plot should be linear and the slope will be the impetus and the intercept the co-volume.

APPENDIX E

EQUATIONS FOR THE HAND CALCULATOR VERSION OF MINICB

As mentioned in the main body of the report an alternate approach to computing the burning rate is to determine the distance burnt, x, which corresponds to each pressure and then compute dx/dt directly instead of using equation (17), $r = (dC_p/dt)/(p*A)$. For the hand calculator version of MINICB this approach was utilized since it requires fewer programming steps. The analysis is identical to the point of finding C_p, equation (14), for each value of pressure. Next, it is necessary to determine values for x for each value of C_p. In the analysis presented earlier, values of x were found by deriving a relation between x and C_p for the specific propellant under investigation based upon initial grain geometry and the relation

$$C_p = \text{density} * \text{Volume Used} \qquad (E-1)$$

Unfortunately, solving the expression resulting from equation E-1 for x was, for most grain geometries, quite complicated, often requiring a numerical scheme. The number of programming steps required for such an operation on a hand calculator was felt to be excessive and would result in a separate program for each grain geometry. Thus, it was decided to make a further simplification in the analysis for the hand calculator version so as to allow for the widest possible range of form functions. Starting with equation (E-1), divide by the original mass of propellant giving equation (E-2).

$$C_p/C = \text{density} * \text{Volume Used}/C \qquad (E-2)$$

Now C_p/C is the mass fraction burnt and will be denoted by M. Also, C, the total mass of propellant, is the density multiplied by the total original volume. Thus, equation (E-2) can be rewritten to produce equation (E-3).

$$M = \frac{\text{density} * \text{Volume Used}}{\text{density} * \text{Total Original Volume}} \qquad (E-3)$$

Canceling density and writing the volumes in terms of volume per grain equation (E-4) can be obtained.

$$M = \frac{\text{Number of Grains} * \text{Volume/grain used}}{\text{Number of Grains} * \text{Original Volume/grain}} \qquad (E-4)$$

Therefore.

$$M * \text{Original Volume/grain} = \text{Volume/grain used} \qquad (E-5)$$

Now the original volume/grain is a constant based upon the original grain geometry and volume/grain used is determined by the original grain geometry and the distance burnt, x. Hence, equation (E-5) could be used to define a relation between M, the mass fraction burnt, and the depth burnt, x. Using this expression to actually calculate x would require as many programming steps as before. However, assuming increasing values of x, a reasonable assumption, a series of values for the mass fraction burnt can be computed. These values may then be fitted empirically to an equation such as

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Routines for such a curve fitting are available for many calculators. The empirical equation can then be used to determine the values of x which correspond to each value of C_p in the program. This approach will reduce the computation of x to an exponentiation and multiplication. Routines for such a curve fitting are available for many calculators. Results for the seven perf grain used in validation 5, Table 5 are shown in Table E-1. Again the analysis is only valid up to the point of slivering which for a seven perf grain occurs at about 80% all burnt.

TABLE E-1.   Fitting to an Equation
$$x = a*M^3 + b*M^2 + c*M + d$$
for a Seven Perf Grain

Web ~ 0.03988 inches

Distance Burnt Inches	Mass Fraction Burnt
.0025	.09195951
.005	.1883845
.0075	.2891035
.01	.3939452
.0125	.502738
.015	.6153106
.0175	.7314915
.01994	.8481996

Values for a, b, c, and d

a = 0.001758388

b = -0.006253527

c = 0.0275523105

d = 0.0000222268

Goodness of Fit: R^2 = 0.999999885

Using the technique above for various other form functions has resulted in similar values for R^2. Thus, it appears that using a cubic equation to relate depth burnt and mass fraction burnt is a reasonable assumption and should provide an acceptable alternative for determining the depth burnt, x, in the hand calculator version of MINICB.

APPENDIX F

HAND CALCULATOR PROGRAM

Listings for the various programs and subprograms which make up the hand calculator version of MINICB are given below for a Hewlett-Packard HP-41C calculator.[*] The remaining section of the Appendix presents comparisons between runs of the hand calculator version and the BASIC version of MINICB and a comparison with CBRED2.

[*] Hewlett-Packard and HP-41C are tradenames of the Hewlett-Packard Corporation. Use of these names does not constitute indorsement by the US Army.

PROGRAM LISTING -- HP-41C

Procedure Name	Function
TINYCB	Calls Various sub-programs
ENDATA	Enter Data
CONST	Computes All Constants
ENPRES	Enter Pressure
PVSR1e	Computes Rates
PVSR2	Interpolation of Rates

MINICB
(Hand calculator version)

```
01*LBL "TINYCB"
02 XEQ "ENDATA"
03 XEQ "CONST"
04 XEQ "ENPRES"
05 XEQ "PVSR1e"
06 FIX 9
07 END
```

```
01+LBL "ENDATA"        31 STO 06
02 120                 32 "FL. TEMP.?"
03 STO 91              33 PROMPT
04 140                 34 STO 07
05 STO 92              35 "COVOLUME?"
06 160                 36 PROMPT
07 STO 94              37 STO 08
08 180                 38 "MOL. WT.?"
09 STO 93              39 PROMPT
10 "IGNITER DATA.,."   40 STO 09
11 AVIEW               41 "WEIGHT?"
12 "IMPETUS?"          42 PROMPT
13 PROMPT              43 STO 10
14 STO 01              44 " GRAIN DATA...."
15 "FL. TEMP.?"        45 AVIEW
16 PROMPT              46 "DIAMETER?"
17 STO 02              47 PROMPT
18 "COVOLUME?"         48 STO 11
19 PROMPT              49 "LENGTH?"
20 STO 03              50 PPOMPT
21 "MOL. WT.?"         51 STO 12
22 PROMPT              52 "GENERAL DATA..."
23 STO 04              53 AVIEW
24 "WEIGHT?"           54 "OBS. PMAX?"
25 PROMPT              55 PROMPT
26 STO 05              56 STO 13
27 "PROPELLANT DATA"   57 "BOMB VOL.?"
28 AVIEW               58 PPOMPT
29 "DENSITY?"          59 STO 14
30 PROMPT              60 END
```

```
01+LBL "CONST"        48 ,
02 12                 49 STO 33
03 ST* 01             50 RCL 14
04 33372              51 16.38786
05 RCL 07             52 /
06 *                  53 RCL 10
07 RCL 10             54 RCL 05
08 *                  55 /
09 RCL 09             56 -
10 /                  57 RCL 05
11 RCL 01             58 RCL 07
12 RCL 35             59 *
13 *                  60 -
14 +                  61 STO 33
15 RCL 11             62 RCL 05
16 16.38786           63 RCL 01
17 /                  64 *
18 RCL 10             65 RCL 33
19 RCL 02             66 *
20 *                  67 RCL 02
21 +                  68 /
22 RCL 05             69 STO 34
23 RCL 03             70 RCL 06
24 *                  71 RCL 06
25 +                  72 1/X
26 /                  73 -
27 STO 30             74 STO 36
28 RCL 13             75 RCL 34
29 RCL 67             76 RCL 33
30 /                  77 /
31 RCL 05             78 STO 37
32 RCL 02             79 RCL 11
33 /                  80 X↑2
34 +                  81 PI
35 RCL 10             82 *
36 RCL 05             83 *
37 +                  84 /
38                    85 STO 35
39 STO 31             86 RCL 12
40 RCL 13             87 *
41 /                  88 RCL 06
42 RCL 30             89 *
43 /                  90 //
44 STO 32             91 RCL 10
45 33372              92 -
46 *                  93 STO 37
47 RCL 09             94 END
```

```
01+LBL "ENPRES"
02 190
03 STO 90
04 "DELTA TIME?"
05 PROMPT
06 STO 16
07 1009
08 ST/ 16
09 "NO. OF PTS?"
10 PROMPT
11 STO 23
12 STO 20
13 .001
14 ST* 20
15 1
16 ST+ 20
17 RCL 20
18 STO 21
19 RCL 37
20 "PP, ( )="
21 ARCL X
22 PROMPT
23+LBL 30
24 RCL 21
25 INT
26 FIX 0
27 "PRES. NO. "
28 ARCL X
29 PROMPT
30 FIX 3
31 STO IND 90
32 1
33 ST+ 90
34 ISG 21
35 GTO 30
36 END
```

```
01+LBL "PVSR1e"        52 +
02 0                   53 RCL 42
03 STO 40              54 +
04 4                   55 STO IND 92
05 STO 41              56 RCL 21
06 100                 57 1.9
07 STO 90              58 X>Y?
08 "1 CONST?"          59 GTO 41
09 PROMPT              60 RCL IND 92
10 STO 42              61 1
11 "X CONST?"          62 ST- 92
12 PROMPT              63 RCL IND 92
13 STO 43              64 CHS
14 "X↑2 CONST?"        65 RCL Z
15 PROMPT              66 +
16 STO 44              67 RCL 16
17 "X↑3 CONST?"        68 /
18 PROMPT              69 STO IND 94
19 STO 45              70 RCL IND 90
20 " .PR.   .RATE."    71 1
21 PROMPT              72 ST- 90
22 RCL 20              73 RCL IND 90
23 STO 21              74 RCL Z
24+LBL 40              75 +
25 RCL IND 90          76 2
26 RCL 33              77 /
27 *                   78 STO IND 93
28 RCL 34              79 CLA
29 -                   80 RCL IND 93
30 RCL IND 90          81 FIX IND 40
31 RCL 36              82 ARCL X
32 *                   83 "|- "
33 RCL 35              84 RCL IND 94
34 +                   85 FIX IND 41
35 /                   86 ARCL X
36 RCL 10              87 PROMPT
37 /                   88 1
38 STO IND 91          89 ST+ 90
39 RCL IND 91          90 ST+ 92
40 3                   91+LBL 41
41 Y↑X                 92 1
42 RCL 45              93 ST+ 90
43 *                   94 ST+ 91
44 RCL IND 91          95 ST+ 92
45 X↑2                 96 ST+ 93
46 RCL 44              97 ST+ 94
47 *                   98 ISG 21
48 +                   99 GTO 40
49 RCL IND 91          100 FIX 9
50 RCL 43              101 END
51 *
```

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```
01+LBL "PVSR2"      50 +                 99 "L "
02 181              51 STO 64            100 RCL 66
03 STO 93           52+LBL 50            101 FIX 4
04 RCL IND 93       53 RCL 23            102 ARCL X
05 5000             54 1000              103 PROMPT
06 /                55 /                 104 ISG 64
07 INT              56 2                 105 GTO 50
08 5000             57 +                 106 FIX 2
09 *                58 STO 22            107+LBL "RATE"
10 5000             59+LBL 51            108 1
11 -                60 100               109 ST- 93
12 STO 60           61 STO 93            110 100
13 RCL 23           62 RCL 22            111 RCL 22
14 1                63 INT               112 INT
15 -                64 ST+ 93            113 -
16 ST+ 93           65 RCL IND 93        114 STO 94
17 RCL IND 93       66 1000              115 RCL 64
18 5000             67 /                 116 INT
19 /                68 RCL 64            117 1000
20 INT              69 INT               118 *
21 5000             70 X<=Y?             119 RCL IND 93
22 *                71 GTO 52            120 -
23 5000             72 ISG 22            121 STO 66
24 +                73 GTO 51            122 RCL IND 93
25 STO 61           74+LBL 52            123 CHS
26 CHS              75 RCL 22            124 1
27 RCL IND 93       76 INT               125 ST+ 93
28 +                77 1                 126 RCL IND 93
29 STO 62           78 -                 127 RCL Z
30 2500             79 RCL 23            128 -
31 X<=Y?            80 X=Y?              129 STO 67
32 STO 55           81 GTO 53            130 1 N
33 RCL 61           82 XEQ "RATE"        131 RCL 66
34 STO 63           83 STO 94            132 *
35 GTO 56           84+LBL 53            133 STO 67
36+LBL 55           85 RCL 23            134 RCL IND 94
37 RCL 61           86 152               135 1
38 2500             87 +                 136 ST- 94
39 +                88 STO 9-            137 RCL IND 94
40 STO 63           89 RCL IND 94        138 INT
41+LBL 56           90 STO 56            139 RCL Z
42 RCL 63           91+LBL 54            140 -
43 50               92 RCL 64            141 RCL 67
44 +                93 INT               142 *
45 1000000          94 1000              143 RCL IND 94
46                  95 *                 144 +
47 RCL 60           96 FIX 2             145 STO 56
48 1000             97 CLA               146 STO
49                  98 ARCL X            147 END
```

To evaluate the hand calculator version of MINICB three different cases were selected. The first two involved a comparison with results from the BASIC version of MINICB. These comparison were performed to investigate the effect of expressing the depth burnt in terms of the mass fraction burnt via a cubic function. Thus, the first comparison was with the the cord burning in a cigarette fashion. This formunction results in a perfect fit between x and M, a=b=d=0 and c = grain length, and hence there should be almost perfect agreement between the results. The only difference is the numerical accuracy between the machines. Results for this comparison are shown in Table F-1 and Figure F-1. In the second comparison, a seven perf grain was used to evaluate the effects of the curve fitting. Details of the curve fitting for this grain are given in Appendix E. Results are found in Table F-2 and Figure F-2. Finally, a comparison was made with results of CBRED2 for a 19 perf grain. The results are given in Table F-3 and Figure F-3. In viewing the results it is important to keep in mind that the hand calculator version was being performed with a very limited number of pressure-time points, 11, 24, and 13 points respectively for the comparisons.

TABLE F-1. Comparison of Calculator Version of
MINICB with BASIC Version for a Cord
Burning in Cigarette Fashion

PRESSURE	RATE		% Difference
psi	in/sec		
	MINICB	MINICB	
	(BASIC)	(CALC)	
2000	58.90745	58.9075	-0.00008
4000	107.5714	107.5713	0.000092
6000	152.6348	152.6348	0
8000	195.8801	195.8801	0
10000	237.7167	237.7167	0
12000	278.4922	278.4922	0
14000	318.1077	318.1077	0
16000	357.5178	357.5178	0
18000	243.6403	243.1748	0.191426

11 data points

91

for Cig. grain — 11 Points
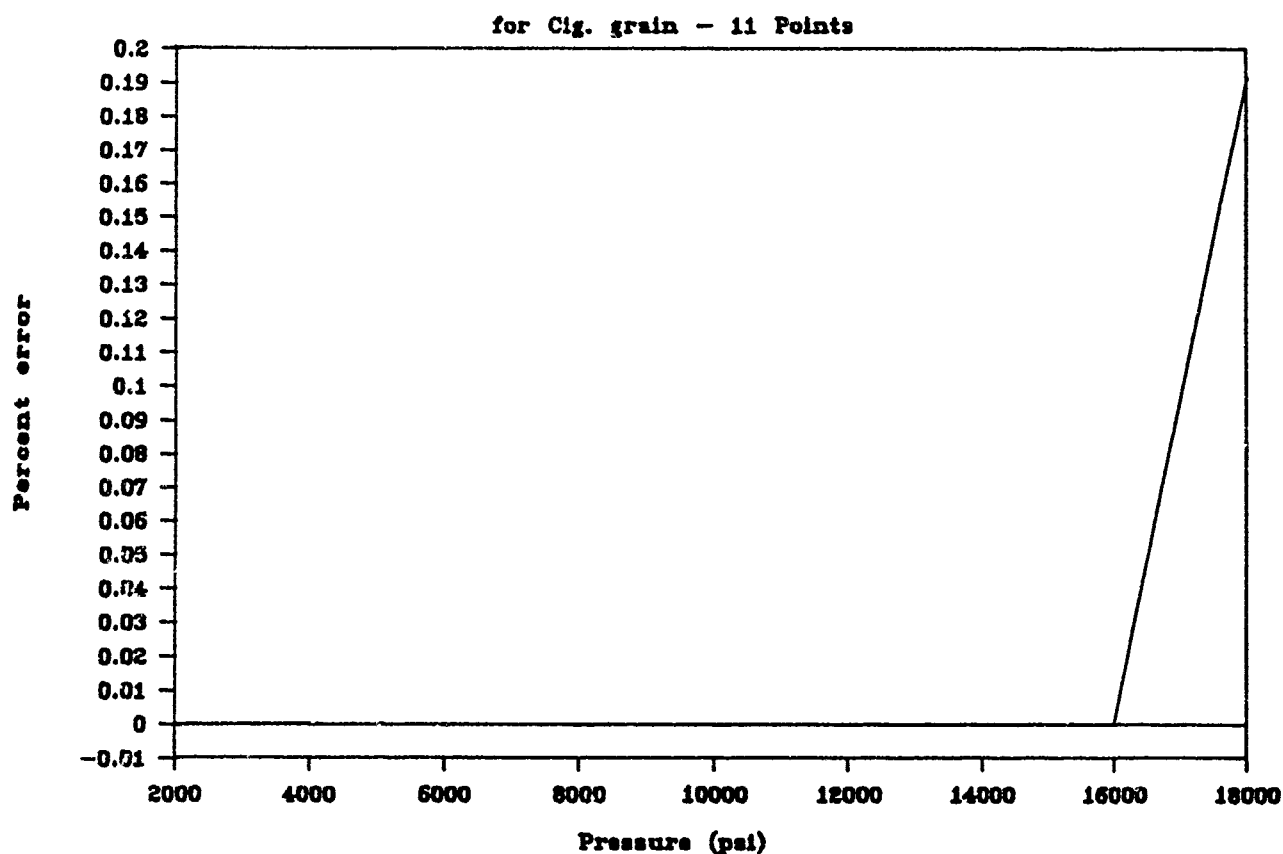
Figure F-1. <u>Comparison of Calculator Version of</u>
<u>MINICB with BASIC Version for a Cord</u>
<u>Burning in Cigarette Fashion</u>

    As an absolute error of 0.02% indicates, the calculator version of MINICB and MINICB produce essentially the same results for the cigarette burning form function.

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TABLE F-2. Comparison of Calculator Version of
MINICB with BASIC Version for a Seven
Perf Grain

PRESSURE psi	RATE in/sec		% Difference
	MINICB (BASIC)	MINICB (CALC)	
5000	1.967996	1.9513	0.857
10000	3.567153	3.5548	0.347
15000	5.055268	5.0577	-0.049
20000	6.464363	6.4880	-0.364
25000	7.824321	7.8724	-0.611
30000	9.142696	9.2167	-0.803
35000	10.4264	10.526	-0.952
40000	11.6847	11.811	-1.068
45000	12.91465	13.066	-1.156
50000	14.12269	14.297	-1.222
55000	15.31281	15.510	-1.274
60000	16.48633	16.706	-1.315
65000	17.63615	17.877	-1.345
70000	18.78596	19.047	-1.371
75000	19.9091	20.191	-1.396
80000	21.01668	21.319	-1.419
85000	22.12426	22.448	-1.440
90000	23.23184	23.576	-1.459
95000	24.29764	24.668	-1.501
100000	25.3589	25.756	-1.542
105000	26.42017	26.844	-1.58
110000	27.48144	27.932	-1.614
115000	28.5427	29.021	-1.647
120000	29.37056	29.88	-1.706

24 data points

93

for 7 Perf grain — 24 Data points
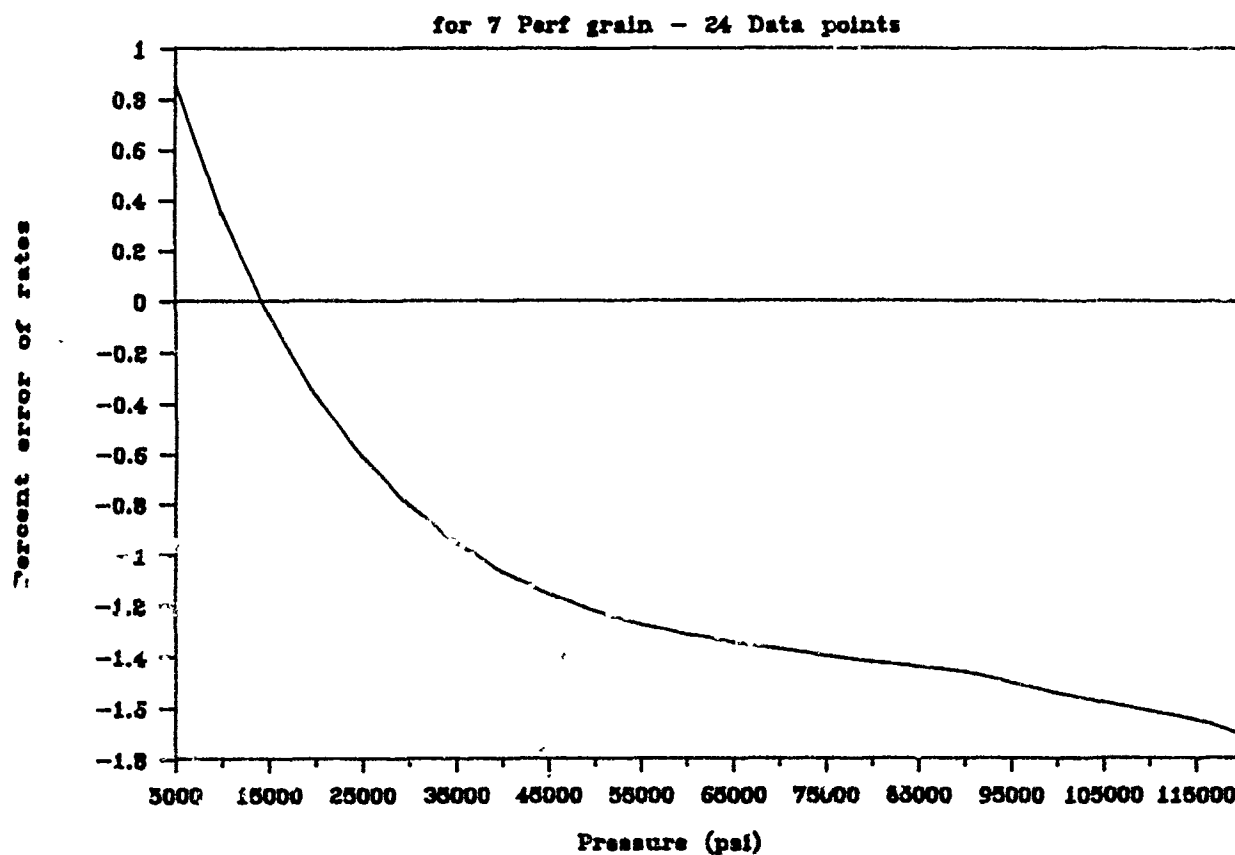
Figure F-2. Comparison of Calculator Version of
            MINICB with BASIC Version for a Seven
            Perf Grain

An absolute error of 1.17% indicates that using a cubic function to fit depth
burnt and mass fraction burnt is a fairly reasonable assumption for multi-perf
grains.

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TABLE F-3. Comparison of Calculator Version of
MINICB with CBRED2 for a Nineteen
Perf Grain

PRESSURE psi	RATE in/sec		% Difference
	MINICB	CBRED2	
5000	1.385	1.378	-0.533
10000	2.554	2.543	-0.452
15000	3.723	3.742	0.505
20000	4.865	4.875	0.216
25000	6.008	6.026	0.304
30000	7.147	7.184	0.52
35000	8.283	8.302	0.232
40000	9.411	9.352	-0.628
45000	10.539	10.377	-1.537
50000	11.294	11.45	.381

13 data points used

95

for 19 Perf grain — 13 Data points
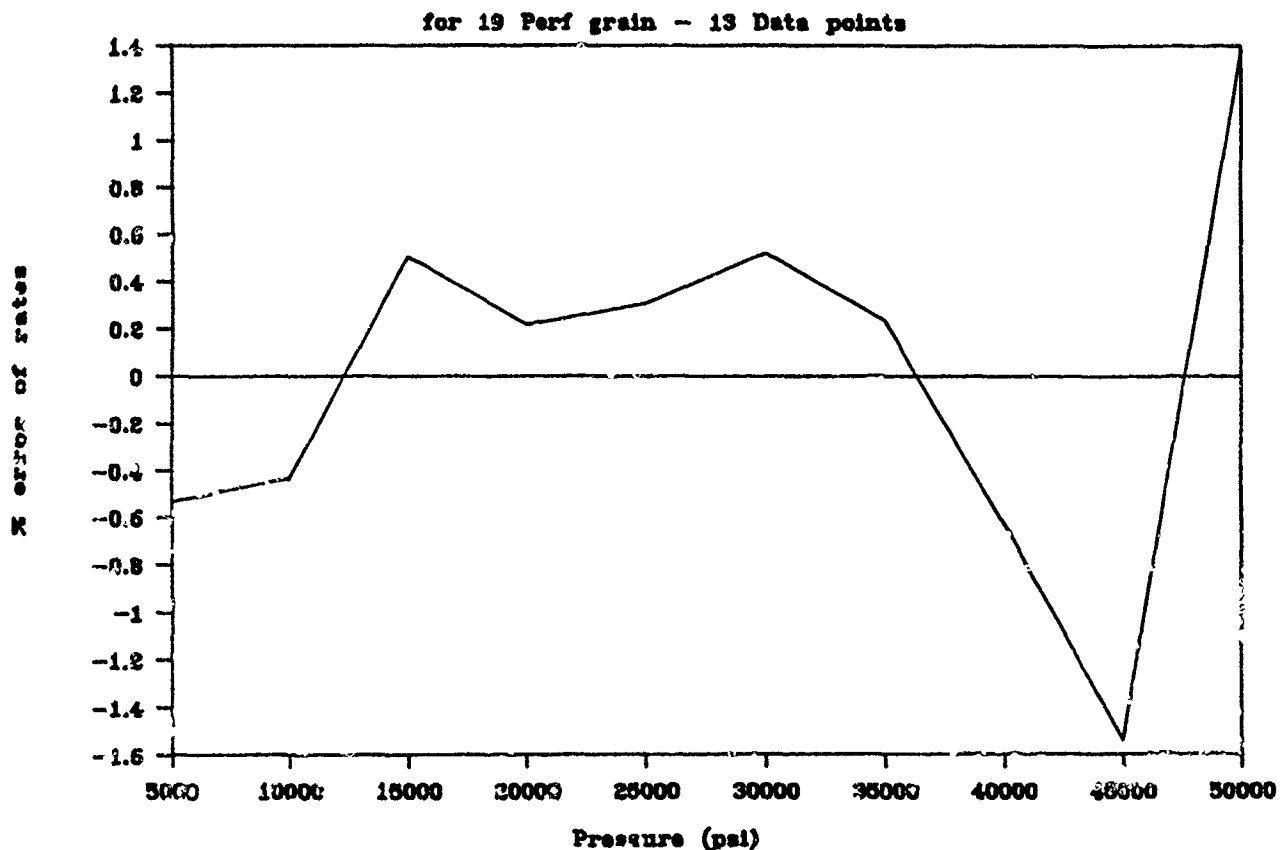
Figure F-3. Comparison of Calculator Version of
MINICB with CBRED2 for a Nineteen
Perf Grain

With an absolute error of 0.63% the agreement between the calculator
version of MINICB and CBRED2 is excellent for this particular comparison
Similar results have been obtained for other form functions and propellants.

Based upon the result of the comparisons it is felt that the calculator
version of MINICB can be used with a high degree of confidence for computing
burning rates from a limited number of data points.

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APPENDIX G

COMPARISON OF THE BASIC VERSION OF MINICB
WITH CBRED2

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For the sake of completeness, the results of MINICB were compared for a limited number of cases with the results from BRL's standard burning rate reduction code, CBRED2, an extension of CBRED. Typical results are presented below. A common experimental pressure-time history obtained from a closed bomb firing was used as input to both programs. Thus, this comparison is relative, comparing only the performance of both programs to each other and not to a burning rate known a priori. Details of the propellant and igniter used in the closed bomb firing are given in Table G-1. Results from the code are presented in Table G-2 and graphically in Figure G-1.

TABLE G-1. Details of Propellant and Igniter
used in Closed Bomb Firing

	Propellant	Igniter
Type:	JA2	FFFG
Weight(lb):	0.1528	0.002205
Density(lb/in^3):	0.0578	------
Gamma:	1.2247	1.25
Impetus(ft-lb/lb):	363241	97500
Co-volume(in^3/lb):	27.42	30.00
Flame Temperature(K):	3437	2000

Number of data points 101

TABLE G-2. Comparison of Burning Rate Between
MINICB and CBRED2 for a 19-perf Grain

Pressure Psi	Rate Inch/s		Percent Difference
	MINICB	CBRED2	
5000	1.335	1.378	3.185
10000	2.489	2.543	2.13
15000	3.734	3.742	0.21
20000	4.833	4.875	0.87
25000	6.072	6.026	-0.75
30000	7.211	7.184	-0.37
35000	8.339	8.301	-1.05
40000	9.404	9.352	-0.55
45000	10.352	10.377	0.24
50000	11.445	11.45	0.044
55000	12.337	12.466	1.05
60000	12.987	12.929	-0.45

Comparison Between MINICB and CBRED2
19 Perf Grain
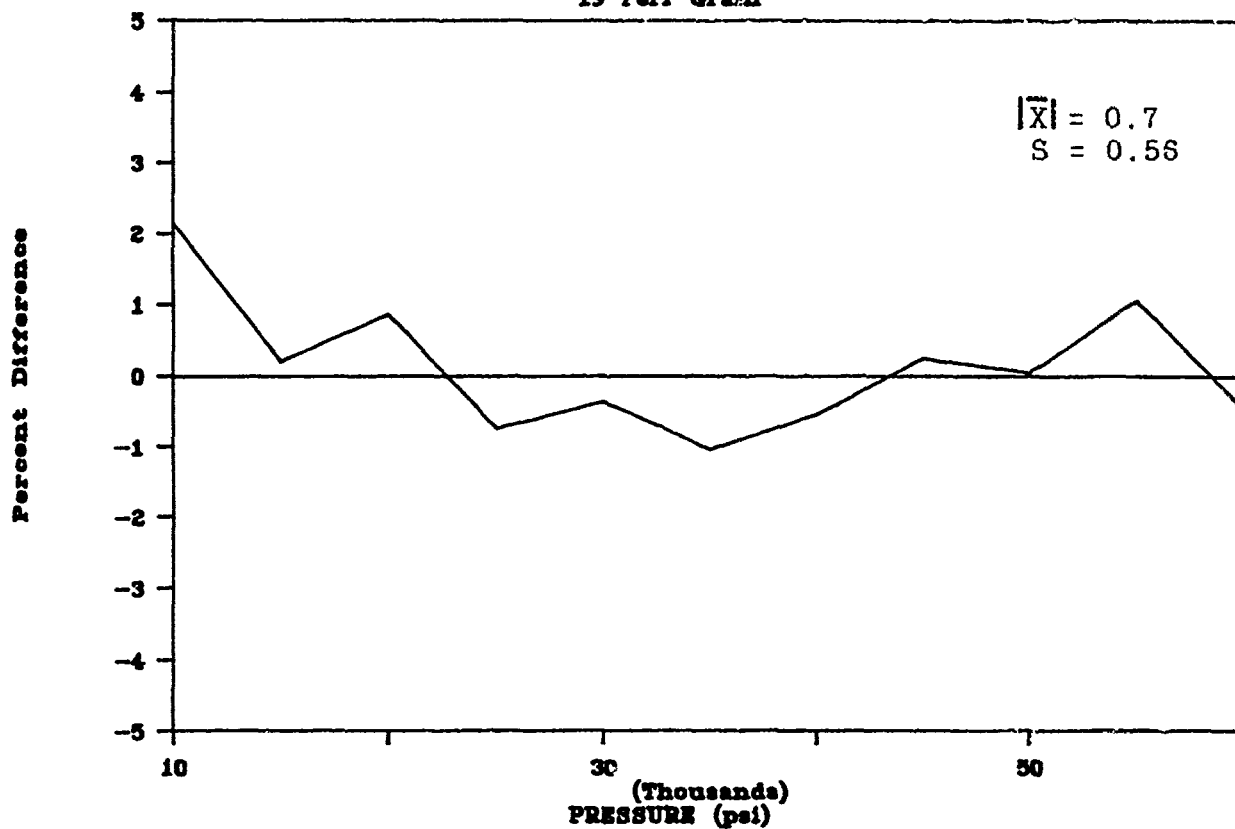

$|\overline{X}| = 0.7$
$S = 0.58$

Figure G-1. Percent Difference in Burning Rate
Between MINICB and C3RFD2

As shown in Table G-2 and Figure G-1 the results for CBRED2 and MINICB
are in excellent agreement with an absolute average error of about 0.9%.
Similar results were obtained for comparisons involving different propellants
and other form functions.

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